UNIVERSIDADE
EDUARDO
MONDLANE

FACULTY OF ENGINEERING
Department of Chemical Engineering
Master in Hydrocarbon Processing Engineering

EVALUATION OF ALTERNATIVE TECHNOLOGY FOR PRODUCED WATER (PW) TREATMENT RESULTING FROM THE NATURAL GAS REFINERY

Case of study: Sasol Petroleum Temane (SPT) – Temane, Inhambane

Dissertation presented to the Post Graduation Department of the Faculty of Engineering of Eduardo Mondlane University - as a partial requirement to obtain a Master's degree in Hydrocarbon Processing Engineering.

António José Faustino

Maputo, November, 2022

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A Dissertation Submitted to the Faculty of Engineering in Partial Fulfilment of the Requirements for the Degree of Master of Hydrocarbon Processing Engineering

António José Faustino

Supervisor: Prof. Doctor Antonio Cumbane (UEM)

Field Supervisor: Eng. Juvencio Massinguil (SPT)

Maputo, November 2022

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AUTHENTICITY STATEMENT

Statement of originality

This is to certify, that the research paper submitted by me is an outcome of my independent and original work. I have duly acknowledged all the sources from which the ideas and extracts have been taken. The thesis is free from any plagiarism and has not been submitted elsewhere for any degree or other purposes.

António José Faustino

DEDICATION

I dedicate:

In memory of my mother Lúcia Costa, my aunty (second mother) Josefina Costa, my grandparents Costa Sousa Simbo and Isabel Lar Joaquim.

To my family and friends.

All colleagues and teachers.

ACKNOWLEDGEMENT

I would like to express special thanks and appreciation to my supervisor Prof. Antonio José Cumbane for providing me an opportunity to work on this research and for outstanding guidance, excellent advice, great encouragement, continuous support, and kind help.

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Thank you all.

ABSTRACT

In oil industry, natural gas process generates several final products, especially methane and condensate, for use in energy production or for household consumption. On the other hand, these processes generate impurities, such as contaminated produced water (PW), when in contact with metal equipment created surface corrosion, destroying the equipment, generating high maintenance costs to companies and causing environment contamination. This study aims to evaluate and find alternatives technologies for the management and treatment of produced water (PW) from Sasol Natural Gas Processing Plant, in order to reduce and control the levels of contaminants before reinjecting into the well and reduce corrosion levels in the equipment. The present study is based on a descriptive case of study with a qualitative approach, where the production process and the produced water from the Sasol Natural Gas Processing Plant were studied. In this process, 10 samples of PW were analyzed, and it was verified that the parameters such as suspended solids, dissolved solids, conductivity, bacteria count, pH, total hydrocarbon and heavy metals (Iron) were at very high levels, outside form what is established by the IFC and MICOA standards. With the injection of corrosion inhibitors, Biocide and Xlamina, it was also possible to verify there were changes or improvements in parameters, except in the reduction bacteria counting until meet the standards. On the other hand, the corrosion inhibitors negatively affected the pH of the water, reduced it from pH=5.4 to the most acidic, pH=4.8. Therefore, from ranking process, as alternatives, to treat the Sasol's produced water, there were selected adsorption, chemical oxidation and hydrocyclone technologies due to their high-ranking values, efficiency on elimination of contaminants listed above and they operate at lower operating and maintenance costs. Based on the results, it can be concluded that the levels of contaminants present in the produced water form Sasol CPF can generate large negative impacts to the environmental, as well as the company's equipment and, application of adsorption, chemical oxidation and hydrocyclone technologies can be one of the best alternatives for control and reduce negative impacts. It can be highlighted that the technologies mentioned above can be modified in order to fulfill the company needs based on company needs - cost reduction, efficiency and mobility - unless is evaluated and safety measures of operators and production processes are guaranteed.

Keywords: Hydrocarbons, Gas, Produced Water (Pw), Water Treatment Technologies

RESUMO

Na indústria petrolífera, o processamento de gás natural gera diversos produtos finais, especialmente metano e condensado, para uso na produção de energia ou para consumo doméstico. Por outro lado, esses processos geram impurezas, como a água contaminada produzida (PW), que quando em contato com equipamentos metálicos criam corrosão superficial, destruindo o equipamento, gerando altos custos de manutenção para as empresas e causando contaminação ambiental. Este estudo tem como objetivo avaliar e encontrar alternativas de tecnologias para o manuseamento e tratamento da água produzida (PW) da unidade Processamento de Gás Natural Sasol, a fim de reduzir e controlar os níveis de contaminantes antes de reinjetar no poço e reduzir os níveis de corrosão no equipamento. O presente estudo baseia-se em um caso descritivo de estudo com abordagem qualitativa, onde foram estudados o processo de produção e a água produzida da unidade de Processamento de Gás Natural Sasol. Nesse processo, foram analisadas 10 amostras de agua produzida, e verificou-se que os parâmetros como sólidos suspensos, sólidos dissolvidos, condutividade, contagem de bactérias, pH, hidrocarboneto total e metais pesados (Ferro) estavam em níveis muito altos, fora do que é estabelecido pelas normas IFC e MICOA. Com a injeção de inibidores de corrosão, Biocídio e Xlamina, também foi possível verificar que não houveram significativas alterações ou melhorias nos parâmetros, exceto na redução da contagem de bactérias até atender aos padrões. Por outro lado, os inibidores de corrosão afetaram negativamente o pH da água, reduzindo-o de pH=5,4 para o mais ácido, pH=4,8. Portanto, a partir do processo de ranking, como alternativas para tratar a água produzida pela Sasol, foram selecionadas tecnologias de adsorção, oxidação química e hidrociclone, devido aos seus altos valores de ranking, eficiência na eliminação de contaminantes listados acima e operam com menores custos operacionais e de manutenção. Com base nos resultados, pode-se concluir que os níveis de contaminantes presentes na água produzida da unidade da Sasol podem gerar grandes impactos negativos para o meio ambiente, bem como equipamentos da empresa e, a aplicação de adsorção, oxidação química e tecnologias hidrociclone podem ser uma das melhores alternativas para controlar e reduzir impactos negativos. Pode-se destacar que as tecnologias mencionadas acima podem ser modificadas para atender às necessidades da empresa - redução de custos, eficiência e mobilidade - ao menos que sejam avaliadas e garantidas as medidas de segurança dos operadores e processos produtivos.

Palavra-Chave: Hidrocarbonetos, Gás, Água Produzida, Tecnologias de Tratamento de Água

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LIST OF ABBREVIATIONS

BAT	-	Best Available Technology Economically Achievable
BBL	-	Barrel of crude oil
BOE	-	Barrel of oil equivalent (1BOE=6MCF)
BPD	-	Barrel per day
MCF	-	1,000 cubic feet (cf) of natural gas (1 MCF=1,000 cf)
MGD	-	Million gallons per day.
BTEX	-	Benzene, toluene, ethylbenzene, and xylenes
CPF	-	Central Processing Facilities
EC	-	Electrical conductivity
EPA	-	Environmental Protection Agency
EIF	-	Environmental Impact Factor
GPA	-	Gas Processors Association
MED	-	Multieffect distillation
MF	-	Microfiltration
MSF	-	Multistage flash distillation
MPPE	-	Macro-porous polymer extraction
MICOA	-	Former Minister of environment coordination, now, Minister of environment and land
NORM	-	Naturally occurring radioactive materials
NF	-	Nanofiltration
PAHs	-	Polyaromatic Hydrocarbons
PW	-	Produced water
RO	-	Reverse osmosis
SPT	-	Sasol Petroleum Temane
TDS	-	Total Dissolved Solid
TSS	-	Total Suspended Solid
TEG	-	Tri-ethylene glycol
THC	-	Total hydrocarbons content
TOC	-	Total organic carbon
UF	-	Ultrafiltration
VCD	-	vapor compression distillation
USA	-	United State of America

CHAPTER I

1.0. INTRODUCTION

1.1. Contextualization

Based on Silva, 2016 (as cited in Ferreira, 2019), In the oil industry, water is present and found in the rock along with oil and natural gas, made up of hundreds of different chemical substances, where most of the constituents are hydrocarbons, the main fuel used as source of energy. In the reservoir, Oil, gas and water are separated into layers where the heaviest, water, is at the bottom of the rock, over it there is oil and gas.

According to (Hedar & Budiyono, 2018), The hydrocarbon to be process, first is extracted as raw material from the gas source and it pass through a separation unit, where the final product, mainly methane, is separated from impurity such as produced water (PW) and some amount for undesired hydrocarbon. Produced Water is water trapped in underground formations that is brought to the surface during oil and gas exploration and production. In traditional oil and gas wells, produced water is brought to the surface along with oil or gas[1].

Produced water comes out of the well with the crude oil or gas during crude oil and gas production. Most of the produced water contain contains soluble and non-soluble oil/organics, suspended solids, dissolved solids closely associated to the geological characteristics of each reservoir, and various chemicals used in the production process[2]. According to Jiménez et al (2017), Produced water is mostly discharged to the immediate aquatic environment and to the soil and plants. The organic and inorganic compounds in produced water have higher toxicity to the environment and discharging PW can pollute the surface and underground water and soil due to its high level of undesired chemical and mineral compound.

Sasol Petroleum Temane (SPT) Company in Mozambique is focused on extraction and processing natural with a purpose of getting methane as main product. During the raw

[1] Produced Water Concept available on http://aqwatec.mines.edu/produced_water/intro/pw/#:~:text=Produced%20water%20is%20water%20trapped,along%20with%20oil%20or%20gas.

[2]Available at https://www.wef.org/globalassets/assets-wef/direct-download-library/public/03---resources/wsec-2017-fs-013-iwwc-og-glossary---final---5.21.18.pdf

gas refinery, the methane is separated from condensate and produced water. The PW comes coupled with some components such us organic, inorganic and volatile compounds that are corrosive to the pipeline & well, liking and contaminate the surrounding soil and water and, the water may also lead to environmental contamination whether it is discharged to surface before any treatment intervention.

This study aims to evaluate alternatives technologies suitable for management and treatment PW, suitable for Sasol's Central Processing Facilities (CPF), in order to reduce and control the contaminants before launch to the environment or re-inject into the well.

The following work is divided in four main chapters, as mentioned. In chapter 1, we have Introduction, which the gives a general idea about the studied topic, the main problems, justification, and the objective of the study. The Chapter 2 talks about literature review, which unfolds basic concept about the research, limitations found during the study to get the results. On the chapter 3 we have the methodology, which shows the different steps used to accomplish the research results such as instruments used, population, sampling method, analysis of data and viability and reliability. Chapter 4 discuss the main results found during the study and the evaluation of alternative technology that can be used to remove the main contaminant in water to reduce environmental impact to the soil, water, air and equipment and avoid environmental charges, followed finally by chapter 5, talks about the final considerations, conclusion, recommendation and references.

1.2. Justification

The produced water, which is separated from the raw gas to get the methane, is first stored in a tank and reinjected into the well to increase the pressure in the gas reservoir to easily restore the desired production level and stimulate the recovery of the available gas, as a way to compensate for the decline of natural gas in the production process.

Before CPF reinject the water into the well, they do not conduct any proper water treatment to remove the contaminants, although the company uses corrosion inhibitors to control the corrosion process of pipeline caused with the produced water. According to observation on production location, it was notable that the effectiveness of the corrosion inhibitors used in reducing corrosion process is quite insignificant and ineffective. This ineffectiveness of the inhibitors and lack of water treatment is increasingly corroding the equipment and continuously destroying the reinjection wells and pipeline, giving a chance of produced water to leak to environment, contaminating the soil, superficial and underground water.

In order to avoid continuous corrosion of the reinjection wells, pipelines and consequent contamination to the superficial and underground water, this study aim to evaluate different alternatives technologies of PW treatment and propose the suitable ones to Sasol CPF, in order to reduce and control the contaminants of re-injection well.

By treating the water, SPT would avoid paying taxes to environmental agencies to compensate for contamination. It will also bring new techniques to the company that could be used in other oil and gas processing plants, both in Mozambique and abroad, provided that the following factors are considered: (1) local conditions of the area, including the type of oil and gas produced and the characteristics of the wastewater generated, (2) cost-effectiveness factors such as capital costs, operation and maintenance costs, and the availability of funding and (3) regulatory requirements and ensure compliance with local laws.

In the academic and scientific area, this study will contribute to the strengthening of practical knowledge related to the applicability of different methods of produced water treatment resulting from oil and gas industries in Mozambique and its insertion in the business and academic society.

The main limitation during the research was the difficulty of having detail data of the following produced water parameter, the total hydrocarbons content (THC), total organic carbon (TOC) ions and content of some heavy metal, because the laboratory analyses report given by the Sasol Central processing Facility did not contain it, due lack of laboratory equipment to carry all such analysis. The parameters data that were not available somehow influenced the judgment of the results and the quality, accuracy and reliability of the study. The only available parameters available that were used in study were, pH, Conductivity, TDS, TSS, Salinity, Conductivity, Dissolved Oxygen, Iron, TEG, Density, Temperature and Bacteria Count.

1.3. Problem

According to Sasol Petroleum Mozambique (2016), the Natural Gas from Sasol Temane & Pande wells has compositions ranging from light to heavy hydrocarbons (up to C9's). The major hydrocarbon component is methane, with a molar composition (mol%) of about 87 to 95%. The remain raw gas component ranging about 5-12% of the raw gas comes with some quantity of impurities, including, inert, carbon dioxide (CO2), produced water, Sulphur and heavy metals. To get the main product, the dry gas methane, the raw material, raw gas from Temane and Pande, gets into the CPF in order to separate the undesired products to the final product, the methane-dry gas, which is sent to the costumers along 900 km pipeline to Sasol Secunda Facility in South Africa, the rest is supplied to *Empresa Nacional de Hidrocarbonetos* (ENH)[3], Mozambican Oil and Gas Company led by the government. Simultaneously when the methane and condensate come out, the impurities, the Produced Water is removed from the separation unit, allocated in PW drams and finally reinjected in to the well. The rejection process of PW when water is pumped down in the well at a pressure that is higher than the pressure of the oil and gas reservoir. This creates fractures in the rock, allowing the water to flow into the reservoir and displace oil and gas.

Based on Da Silva et all (2018), the PW is generally the largest effluent generated by oil and gas companies and it has considerable number of volatile compounds, hydrocarbons, salt content, dissolved gases, other toxic substances, dissolved and suspended solids. The PW when in contact with pipelines and wells might cause corrosion, because, the PW might contain high levels of dissolved salts, such as chlorides and when it is influenced by temperature and pressure, can be highly corrosive to metal surfaces. Therefore, if PW comes into contact with metal pipes and wells, the chloride ions can react with the metal surface, causing the metal to corrode and weaken over time. PW may also contain hydrogen sulphide (H2S) and when it reacts with metal surfaces, it can cause sulphide stress corrosion cracking (SSCC), a form of corrosion that can cause rapid and catastrophic failure of the metal. Therefore, if a PW contain these elements is not well treated before being disposed in the environment may contaminate underground water and consequently affects public health and organization economy, though taxes payment and equipment maintenance.

[3] https://www.enh.co.mz

To avoid future health problems and regulation compliance, Sasol's CPF uses reinjection method [4]to dispose the PW into the well, besides disposing into environment, even without a previous treatment. In the reinjection process, the water is reinjected into a designated well, leading the water of the reservoir, in place of disposing it to environment, without any previous treatment. The injected water can help to sweep the oil and gas towards the production wells, making it easier to extract. One of the purpose reinjection Process is providing a safe and environmentally responsible disposal option that minimizes the risk of contamination of surface and groundwater resources. The other purpose to increase pressure in the oil and gas reservoir, thereby restoring the desired level of production and stimulating the recovery of additional available oil and gas. This method helps to improve the recovery of oil and gas remaining in the reservoir and helps to compensate the natural decline in the oil and gas production field by improve the recovery factor of the reservoir, which is the percentage of oil or gas that can be recovered from the reservoir. Therefore, Increasing the recovery factor can extend the life of the reservoir and increase the overall production of oil and gas from the field.

However, on the other hand, the PW reinjection process conducted at Sasol does not substitute any treatment method and doesn't even guarantee complete safety in term of environmental contamination reduction, because the reinjected water still contains some contaminants elements, such as chemicals elements, heavy metals, TSS, TDS, among others) and organic contaminants. These elements present in water can react with and corrode the wells and pipeline and, over long period, due to the well damage the water might leak underground and contaminate the soil and underground water.

Although, the CPF before reinjecting the water into the well, uses corrosion inhibitors to control the corrosion process of pipeline. Even though, it is notable that the effectiveness corrosion inhibitors in reducing corrosion process is quite insignificant and ineffective, because the corrosion process does not stop and one of the reinjections well has already closed, due the corrosion. The corrosion inhibitors work by forming a protective layer on the surface of metal pipes and equipment in oil and gas production systems. This protective layer, acts as a barrier between the metal surface and the corrosive environment, preventing or slowing down the corrosion process. The problem is that these corrosion inhibitors can be less effective in produced water treatment because produced water normally contain a

[4] PW Reinjection Process or Method is a method of disposing of produced water (PW) generated during oil and gas production by injecting it back into the same reservoir from which it was extracted.

range of contaminants, including dissolved salts, gases, and organic compounds, which can interfere with the effectiveness of corrosion inhibitors. In one hand, the high levels of dissolved salts can form a protective layer on the surface of metal pipes and equipment, which can prevent the corrosion inhibitor from reaching the metal surface and inhibiting corrosion. On other hand, the presence of hydrogen sulphide and carbon dioxide, can react with the corrosion inhibitors and reduce their effectiveness. Is also important to consider that, the effectiveness of corrosion inhibitors the temperature, pressure, and flow rate of gas in the well.

As Sasol Petroleum Temane still opening more and new wells to explore more gas for next future energy production, consequently, more produced water, (PW) might come out during the next time of gas exploration and production. As the amount of water coming with the raw natural gas will significantly increase, as consequence, the produced water might also increase and using only a corrosion inhibitor to reduce the impact of corrosion on the pipe might not be sustainable for infrastructure safety, company economy and effort and for the environment protection.

The way to avoid future environmental problems for the production process and environment in general, is imperative do find technology to control and reduce contaminants contents present into the PW earlier before, so that it can be re-injected into well or can be re-used or disposed of, safely. In this perspective, the following question arises that allows guiding the work:

What are the treatment technologies alternatives for treatment of Natural Gas Produced Water (PW) that can effectively control and prevent corrosion of pipes and pumps in the CPF and reduce environmental contamination?

1.4. Hypothesis

There exist treatment technologies alternatives for treatment of Natural Gas Produced Water (PW), that can effectively control and prevent corrosion of pipes and pumps in the CPF and reduce environmental contamination.

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1.5. Objectives

1.5.1. Main Objective

The main objective of this study is to propose treatment technologies alternatives for Natural Gas Produced Water (PW) that can effectively control and prevent corrosion of facility pipes and pumps in the Sasol Central Processing Facilities CPF and reduce environmental contamination.

1.5.2. Specific objective

- To analyse the data on the composition and characteristics of the Produced Water (PW) from SPT's Natural Gas in compliance National and international regulations;
- To identify the main environmental negative impact associated with the Produced Water (PW) SPT's Natural Gas.
- To evaluate the efficiency of corrosion inhibiting agents used in SPT, and their influence on reducing corrosion in the pipes.
- To evaluate and propose different alternative technologies for management and treatment of natural gas PW that Sasol's CPF can adopt to avoid future contamination to environment.

CHAPTER II

2.0. LITERATURE REVIEW

To contextualize the present work, the theoretical aspects approach were divided in order to contemplate the most relevant concepts about natural gas, its production and composition, and yet, the produced water and its appropriate treatment methods based on its final destination.

2.1. Natural gas production

Natural Gas – is a mixture of gases which are rich in hydrocarbons such as methane, nitrogen, carbon dioxide etc., which are found deep inside the earth near other solid & liquid hydrocarbons beds like coal and crude oil. After extraction, the gas is processed and converted into cleaner fuel for consumption. For the The economic times (n.d.)[5], the largest component of natural gas is methane (CH4), accompanied with other products such as propane, ethane, butane, carbon dioxide, nitrogen and some water vapor. The natural gas is mainly, used as fuel for generating electricity and heat. In other hand, the natural gas can also, be compressed to form CNG and liquefied to form LNG, to be used as fuel for vehicles and domestic purpose and also for electricity and as fuel for ships, trucks, and buses. Finally, it can also, be used on ammonia-based fertilizers production.

2.1.1. Gas Production Principle and Main Natural Gas Products

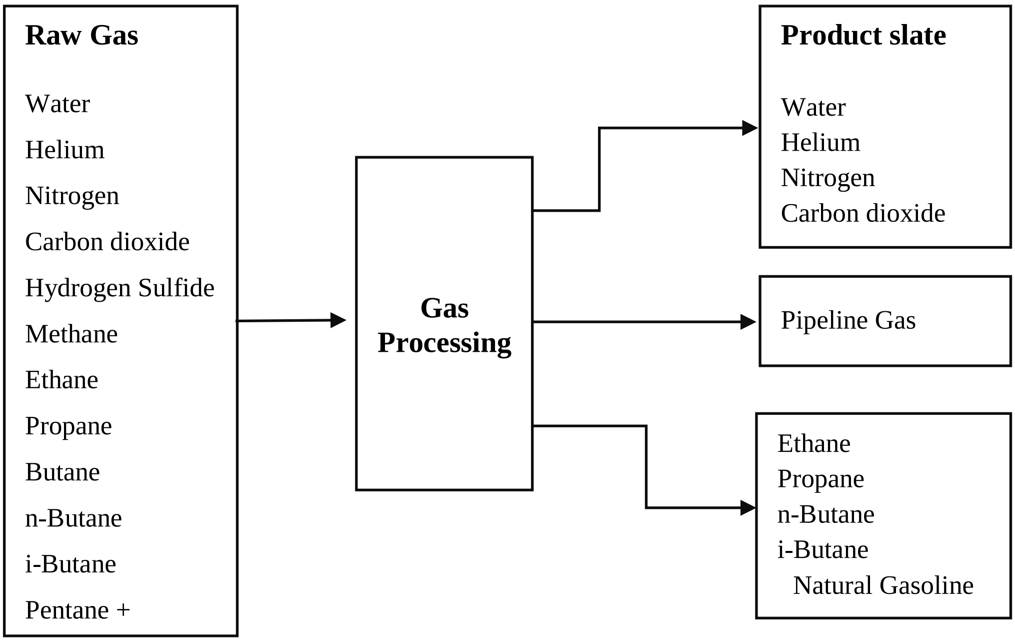
According to Kidnay & Parrish, (2006), the natural gas has for different applications, as fuel or even as petrochemical feedstock. Before use, it needs to be processed industrially, to get to the final product, because of three basic reasons:

a. **Purification** - Removal of materials, valuable or not, that inhibit the use of the gas as an industrial or residential fuel;
b. **Separation** - Splitting out of components that have greater value as petrochemical feedstock, standalone fuels (e.g., propane), or industrial gases (e.g., ethane, helium)
c. **Liquefaction** - Increase of the energy density of the gas for storage or transportation

[5] https://www.eia.gov/energyexplained/natural-gas/

Depending on the situation, the production process may be via either separation or purification. For example, if a small amount of H_2S is removed, incinerated, and vented to the atmosphere, the process is purification, but if large amounts of H_2S are removed and converted to elemental sulfur, often a low-priced commodity, the process is considered separation. The **Figure *1***, below provides an overview of the materials present in natural gas and the slate of possible products from the gas plant (KIDNAY & PARRISH, 2006).

Figure 1 - Generic raw gas and product slate



Source: (Kidnay & Parrish, 2006)

According to Kidnay & Parrish (2006), the main products found from natural gas process are:

a. **Methane** – **methane** is used as a fuel; it is the major constituent of pipeline quality natural gas. Considerable quantities of methane is used as feedstock in the production of industrial chemicals, principally ammonia and methanol.

b. **Ethane** – is mainly used to produce ethylene, a feedstock to make polyethylene.

c. **Propane** – The principal uses are petrochemical (47%), residential (39%), farm (8%), industrial (4%), and transportation (2%) (Florida Propane Gas Council, 2005).

d. **Ethane–Propane Mix** - When LNG is fractionated into various hydrocarbon streams, the butanes along with part of the propane are sometimes separated for use in local markets because they are transportable by truck. The remaining light ends, an ethane−propane mix (E-P mix), is then pipelined to a customer as a chemical or refining feedstock.

e. **Isobutane** –The three primary markets for isobutane are as a feedstock for MTBE (methyl tertiary butyl ether) production, as a feedstock in the production of reformulated gasoline, and as a feedstock for the production of propylene oxide.

f. **n-Butane** - Domestic usage of n-butane is predominantly in gasoline, either as a blending component or through isomerization to isobutane. Specially produced mixtures of butanes and propane have replaced halocarbons as the preferred propellant in aerosols.

g. **Natural gas liquids (NGL**)-NLG include all hydrocarbons liquefied in the field or in processing plants, including ethane, propane, butanes, and natural gasoline. Such mixtures generated in gas plants, are usually referred to “raw product.”

h. **Natural gasoline** - a mixture of hydrocarbons that consist mostly of pentanes and heavier hydrocarbons. The major uses of natural gasoline are in refineries, for direct blending into gasoline and as a feedstock for C5/C6 isomerization, also used in the petrochemical industry for ethylene production.

i. **Sulfur** - Currently, about 85% comes of sulfur production comes from natural gas processing plants. It can be converted from to H_2S to elemental sulfur.

2.1.2. Natural Gas Product specification

The composition of natural gas varies from location to location and the specifications for the gas products are generally in composition and performance criteria. The typical specifications for quality gas product for pipeline transportation are listed on below

*Table **1***.

Table 1 - Specifications for pipeline quality gas

Major Components	Minimum Mol %	Maximum Mol %
Methane	75	None
Ethane	None	10
Propane	None	5
Butanes	None	2
Pentanes and heavier	None	0.5
Nitrogen and other inerts	None	3
Carbon dioxide	None	2-3
Total diluent gases	None	4-5
	Trace components	

Hydrogen sulfide	0.25-0.3 g/100 sef (6-7 mg/m3)
Total Sulfur	5-20 g/100sef (115-460 mg/m3)
Water Vapor	4.0-7.0 lb/MM sef (60-110 mg/m3)
Oxygen	1.0%

Source: (Kidnay & Parrish, 2006)

2.2. Produced Water

Produced water is water from underground formations brought to the surface during oil or gas production. The water is disposed with some oil and gas particle after its separation from the real oil and gas. During oil and gas exploration other forms of wastewater are produced, these include injected water, little quantity of water that is condensed and traces of some chemicals used among which produced water is the highest generated by-product. (HEDAR & BUDIYONO, 2018)

According to Jiménez et al (2017), depending on the geographic location of the field, the geological formation, the extraction method and the type of hydrocarbon, the PW might contains some of the chemical characteristics of the hydrocarbon and other major groups of constituents such as: Salts (expressed as salinity, total dissolved solids (TDS), or electrical conductivity), BTEX (benzene, toluene, ethylbenzene, and xylenes), PAHs (polyromantic hydrocarbons), Organic acids, Phenol, inorganic and organic compounds (e.g., chemicals that cause hardness and scaling such as calcium, magnesium, sulfates, and barium).

2.2.1. Characterization of produced water from gas field

According to Hedar & Budiyono (2018), the composition of PW from different sources can vary by order of magnitude. However, PW composition is qualitatively similar to oil and/or gas production. Produced water is resulting from natural gas process might come with some condensate. Produced waters from gas production have higher contents of low molecular-weight aromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylene (BTEX) than those from oil operations, hence they are relatively more toxic than produced waters from oil exploration. (GUERRA, DAHM, & DUNDORF, 2011).

Studies indicate that the produced waters discharged from gas/condensate platforms are about 10 times more toxic than the produced waters discharged from oil platforms (GUERRA, DAHM, & DUNDORF, 2011). However, for produced water discharged offshore, the volumes from gas production are much lower, so the total impact may be less.

The chemicals used for gas processing include dehydration chemicals, hydrogen sulfide-removal chemicals, and chemicals to inhibit hydrates formation (STEPHENSON, 1992).

According to (Hedar & Budiyono, 2018), the major compounds of produced water include: (a) Dissolved and dispersed oil compounds; (b) Dissolved formation minerals; (c) Production chemical compounds; (d) Production solids (including formation solids, corrosion and scale products, bacteria, waxes, and asphaltenes); (d) Dissolved gases

According to (Hedar & Budiyono, 2018), A wide range of gas treatment chemicals is used in gas fields including methanol, ethylene and Triethylene glycol. About one-third of these chemicals are disposed in produced water. Volatile components concentrations in produced water from gas fields are higher than those in produced water from oilfields. The *Table 2* shows concentrations of constituents in produced water from gas fields.

Table 2 - Concentrations of constituents in produced water from gas fields

Parameter	Minimum	Maximum	Parameter	Minimum	Maximum
pH[a]	4.4	7.0	Iron[a]	ND	1100
pH[b]	3.1	6.47	Iron[b]	39	680
Conductivity[a] (umhos/cm)	4200	180,000	Lead[b]	<0.2	10.2
Conductivity[b] (umhos/cm)	136,000	586,000	Lithium[b]	18.6	235
Alkalinity[b]	0	285	Magnesium[a]	0.9	4300
TDS[a]	2600	310,000	Magnesium[b]	1300	3900
TDS[b]	139,000	360,000	Manganese[a]	0.045	6.5
TSS[a]	14	800	Manganese[b]	3.59	63
TSS[b]	8	5484	Nickel[a]	ND	0.02
BOD5[a]	75	2870	Nickel[b]	<0.08	9.2
COD[a]	2600	120,000	Potassium[b]	149	3870
Aluminum[a]	ND	0.4	Silver[b]	0.047	7
Aluminum[b]	<0.50	83	Sodium[a]	520	45,000
Arsenic[a]	0.004	1	Sodium[b]	37,500	120,000
Arsenic[b]	<0.005	151	Strontium[a]	–	6200
Barium[a]	ND	26	Sulfate[a]	<0.1	47
Barium[b]	9.65	1740	Sulfate[b]	ND	19
Boron[a]	ND	56	Tin[a]	ND	1.1
Bromide[b]	150	1149	Zinc[a]	ND	0.022
Cadmium[a]	ND	0.015	Zinc[b]	<0.02	5
Cadmium[b]	<0.02	1.21	TOC[a]	67	38,000
Calcium[a]	ND	25,000	Surfactants[b]	0.08	1200
Calcium[b]	9400	51,300	Benzene[a]	1.8	6.9
Chloride[a]	1400	190,000	Benzene[c]	<0.010	10.3
Chloride[b]	81,500	167,448	Toluene[a]	0.857	3.37
Chromium[a]	ND	0.03	Toluene[c]	<0.010	18
Copper[a]	ND	0.02	Oil/grease[a]	6	60
Copper[b]	<0.02	5	Oil/grease[b]	2.3	38.8

a[6]
b[7]
c[8]

Source: (Hedar & Budiyono, 2018)

[6] Parameter value based on FILLO & EVANS (1990)
[7] Parameter value based on United States Environmental Protection Agency (USEPA), (2000)
[8] Parameter value based on SHEPHERD et al. (1992)

2.2.2. Regulations and discharge limits to consider for produced water discharging

Based on Jiménez et al (2017), PW is conventionally treated through gravity-based separation and discharged into the environment in offshore platforms or reinjected into the soil in onshore ones. It is commonly known that organic components, heavy metals and production chemicals have consequences equipment in oil and gas facility, on reception body and living organisms (see resume in ***Table 23***, in appendices page), since metals and hydrocarbons from oil platforms are very toxic to the ecosystem.

Basically, Flores, (2004) refers that the major constituents of co-produced water with oil and natural gas include (1) salt components such as salinity, TDS, and electrical conductivity (EC); (2) oil and grease as a measure of the organic chemical compounds; (3) inorganic and organic compound chemical additives used in drilling, completion, stimulation, and operation of the well, and; (4) naturally occurring radioactive materials (NORM) (example: uranium and thorium). Before discharge or re-inject the water to the environment, PW should meet certain standards, to avoid soil, surface water and underground water pollution. When the PW meets the standards and legislation, it might be reused for any purpose: irrigation, re-injection in well to maintain hydraulic pressure and improve the recovery of gas and oil or even for cleaning purpose, if necessary

According to Environment Protection Regulations 2003 (G.N. No. 44 of 2003) for effluent discharge published by FAO (2013)[9], Environmental and Effluent Emission from MICOA (2004) [10] and Standards for Emissions, Effluent and Waste Levels from Onshore Oil and Gas Development from IFC (2007)[11] show some comparison of parameter of produced water that must be followed and controlled in order avoid control and environmental contamination, as show on ***Table 22*** available one appendices below.

In these 3 standards some parameter has completely different values, while most has the values range, for example, the pH varies from 6-9, the TSS between 30-50 mg/l or ppm, total hydrocarbon lower than 10 mg/l, chloride between 600-1200 mg/l, the density must not pass 1020 kg/m3 = 1020 mg/l, the TDS, conductivity must not pass between 670 -1675mg/l and 1000 -2500 µS/cm respectively, the heavy metal including Arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, vanadium, sodium and zinc must not pass

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[9]Available at: http://www.fao.org/faolex/results/details/en/c/LEX-FAOC052519/
[10]Availableat:http://www.impacto.co.mz/wpcontent/themes/Arpora2_1_0/pdf/Padroes%20de%20Qualidade/DECRET~3.PDF
[11]Available at: https://www.ifc.org/wps/wcm/connect/f0167aa2-edd2-4b46-aeb6-b2935a9e6c95/Final%2B-%2BOnshore%2BOil%2Band%2BGas%2BDevelopment.pdf?MOD=AJPERES&CVID=jkD2DAU&id=1323153172270

5 mg/l and salinity must not pass 40 ‰. More data can be found one the ***Table 22*** available on appendices.

According to Kidnay & Parrish (2006) and Hedar & Budiyono (2018), The effect of produced water in a certain environment depends mostly on the physical, chemical and biological composition of such environment and raw material that come from the source. Findings indicate that in spite of all the level of toxicity of produced water effluent, there is paucity of information on their real impact on the exposed ecology. Produced water from oil and gas industries often is permitted to be discharged to the environment, only if it obeys the requirement shown in ***Table 22***, available on appendices page.

2.2.3. Environmental impact of the produced water

Based on Flores, (2004) and Hedar & Budiyono (2018), Produced water is a mixture of inorganic and organic compounds. Salinity is a general attribute of produced water. Salinity is related to total dissolved solids (TDS) in water. Salinity is a measure of the concentration of dissolved salts in water, including both organic and inorganic substances. TDS is a measure of the total amount of inorganic and organic substances present in water, including salts, minerals, metals, and other substances. In general, the higher the salinity of water, the higher the TDS concentration will be. This is because salts are a major component of TDS, and are the primary contributor to the conductivity of water. The TDS level of water is typically measured in parts per million (ppm) or milligrams per liter (mg/L). In some cases, TDS may be used as a proxy for salinity, as there is a strong correlation between the two. Normally the TDS can vary in produced waters from 1.000-400.000 mg/L. According to EPA (2001), the TDS can be obtained by conductivity, by converting conductivity in µS/cm to TDS in mg/l. therefore the standard TDS for produces is 675mg/l to 16750mg/l resulting from 1000-2500 µS/cm, form this formula: Conductivity (µS/cm) x 2/3 = Total Dissolved Solids (mg/l), based on (EPA, 2001).

Environmental effect of produced water salts can occur in all regions where oil and gas have been produced. Sodium is a major dissolved constituent in most produced waters and it causes substantial degradation of soils through altering of clays and soil textures and subsequent erosion. High sodium levels compete with calcium, magnesium, and potassium for uptake by plant roots, therefore, excess sodium can prompt deficiencies of other cations. Elevated levels of sodium also can cause poor soil structure and inhibit water infiltration in soil. Produced water salts seem to have the most wide-ranging effects on soils, water quality, and ecosystems. It is as a major contributor of toxicity. Salinity is higher in produce water than some sea water which could result to aquatic destruction in fresh water. Inorganic ions (e.g., sodium, potassium, calcium, and chloride) are not concern in produced water discharges to the ocean but are of environmental concern when the treated water discharged to land or surface fresh or brackish water.

Some produced waters contain chemicals that are highly toxic to sensitive marine species, even at low concentrations. When discharge is to shallow, enclosed coastal waters, or when discharge is of a low-density produced water in an area with low water turbulence and current speeds, concentrations of produced water chemicals may remain high for long enough to cause ecological harm. The chemicals of greatest environmental concern in produced water, because their concentrations may be high enough to cause bioaccumulation and toxicity include aromatic hydrocarbons, some alkylphenols, and a few metals. (NEFF, LEE, & DEBLOIS, 2002).

Based on Neff, Lee, & Deblois (2002), Most metals and naturally-occurring radionuclides are present in produced water in chemically reactive dissolved forms at concentrations similar to or only slightly higher than concentrations in seawater and, therefore, are unlikely to cause adverse effects in the receiving water environment. Heavy metal toxicity is less than nonpolar organics in produced water. If produced water is discharged to shallow estuarine and marine waters, some metals and higher molecular weight aromatic and saturated hydrocarbons may accumulate in sediments near the produced water discharge, possibly harming bottom living biological communities.

According to Jacobs, Grant, Kwant, & Marquenie (1992). Produced water from gas production tend to have higher content of low molecular weight aromatic hydrocarbon such as benzene, toluene, ethylbenzene, and xylene (BTEX) than produced water from oil production. Studies indicate that the produced water discharge from gas/condensate platform are about 10 times more toxic than produced water discharged from oil platform.

Below is shown in tables, a summary of main produced water parameter to be considered based on regulation and standards in liquid effluents from Onshore Oil and Gas Production, mainly produced water (PW) and how they react when get in touch with facilities, soil & water and generate impact to the production process and the environment.

2.2.4. Produced water management and treatment

According to (Takur & Satter, 1998) Produced water management has challenged Oil and Gas companies to find management practice that would help on reducing its effect on the environment, and keeps costs to the minimum to the operator. Some efforts were implemented and gravity separation was the only treatment method at that time. Water flooding was done in some arid areas by re-injecting PW to increase production of oil and gas reservoirs. In order to minimized impact of the produced water to environment, were created the Environmental Protection Agency (EPA) in 1974. EPA has described the Best Available Technology Economically Achievable (BAT) for proposing appropriate effluent limitations. It was realized that PW can be used for other purposes by recycling and can also be minimized or in last instance disposed:

a. **Recycle -** Recycling or reuse of produced water for other purpose, after treatment. It can be achieved by re-injection into wells for enhanced oil recovery. PW can be used for agricultural purposes: irrigation, livestock watering, aquaculture, and hydroponic vegetation. At low cost, the PW can also be reinjected to the well. For any recycle purpose is better to treat the water before use to ensure that water is clean enough, and avoid impacts on plants and animals. Salinity and sodicity are the most major problems associated with PW for agricultural purposes. For drinking purposes, the PW treatment must be so accurate and the best in order to avoid contamination.

a. **Minimization -** Minimization is the reduction in the amount of PW generation. It is the best management option as compared to others, and can be achieved by mechanical blocking devices in wells to reduce the volume of water entering the well. They can be used in new wells; however, they are difficult to install in existing wells. Using other materials as substitute for water in frac fluids, like CO2, nitrogen, and gel in place of water is also considered. They can minimize the water volume; however, they can also be ineffective and costly.

b. **Disposal** – This option is the last implemented. The disposal process basically related discharging the PW into the receiving bodies after some treatment and are mostly, applied on for offshore facilities and less for onshore facilities.

2.2.5. Conventional treatments of PW for Onshore Gas Processing

According to Hebron Project. (2011) using the 3 strategies for managing PW, the Minimization, Recycle or reuse and disposal, there is a need for specific treatment before choose the method in order to comply with legal obligations, avoid negative impacts to the environment and to production facilities or in order to allow its reuse without causing damage to the processes in which this water will be used as an input.

Based on Daniel, Langhus, & Patel (2005) The general objectives for operators treating produced water are: de-oiling (removal of dispersed oil and grease), desalination, removal of suspended particles and sand, removal of soluble organics, removal of dissolved gases, removal of naturally occurring radioactive materials (NORM), disinfection and softening (to remove excess water hardness). To meet up with these objectives, operators have applied many standalone and combined physical, biological and chemical treatment processes for produced water management. Some of these technologies are reviewed in this section and compared in different below tables in term cost, efficiency and efficacy.

2.2.5.1. Membrane filtration technology

According to Igunnu & Chen (2014), Membranes are microporous films with specific pore ratings, which selectively separate a fluid from its components. There are four established membrane separation processes, including microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF). RO separates dissolved and ionic components, MF separates suspended particles, UF separates macromolecules and NF is selective for multivalent ions. MF and UF can be used as a standalone technology for treating industrial wastewater, but RO and NF are usually employed in water desalination.

Membrane technology operates two types of filtration processes, cross-flow filtration or dead-end filtration, that can be a pressure (or vacuum)-driven system. The membrane filtration technology can be classified indifferent technology type according what is described below and shown on the ***Table 24***, available on appendices.

2.2.5.2. Thermal treatment technologies

Thermal treatment technologies of water are employed in regions where the cost of energy is relatively cheap. Thermal separation process was the technology of choice for water desalination before the development of membrane technology. Multistage flash (MSF) distillation, vapor compression distillation (VCD) and multi effect distillation (MED) are the major thermal desalination technologies. Hybrid thermal desalination plants, such as MED–VCD, have been used to achieve higher efficiency. Although membrane technologies are typically preferred to thermal technologies, recent innovations in thermal process engineering make thermal process more attractive and competitive in treating highly contaminated water (Igunnu & Chen, 2014). Thermal treatment technologies can be classified according what is shown on the ***Table 25***, available one appendices page.

2.2.5.3. Other produced water treatment technologies

2.2.5.3.1. Biological aerated filters

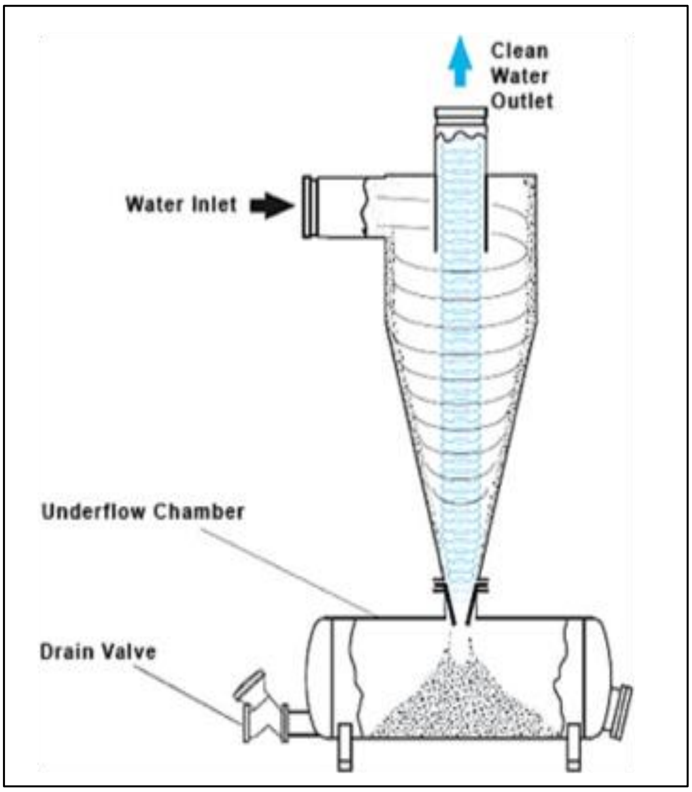
Biological aerated filter (BAF) is a class of biological technologies which consists of permeable media that uses aerobic conditions to facilitate biochemical oxidation and removal of organic constituents in polluted water. Media is not more than 4 in in diameter to prevent clogging of pore spaces when sloughing occur (Igunnu & Chen, 2014). BAF can remove oil, ammonia, suspended solids, nitrogen, chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metals, iron, soluble organics, trace organics and hydrogen sulfide from produced water (Igunnu & Chen, 2014). It is most effective for produced water with chloride levels below 6600 mg/l (Igunnu & Chen, 2014). This process requires upstream and downstream sedimentation to allow the full bed of the filter to be used. Removal efficiencies of up to 70% nitrogen, 80% oil, 60% COD, 95% BOD and 85% suspended solids have been achieved with BAF treatment (Sun, Wang, Liu, et al, 2007). Water recovery from this process is nearly 100% since waste generated is removed in solid form (Igunnu & Chen, 2014).

BAF usually have a long lifespan. It does not require any chemicals or cleaning during normal operations. Its power requirement is 1–4 kWh/ day, and capital accounts for the biggest cost of this technology. Solids disposal is required for accumulated sludge in sedimentation basins and can account for up to 40% of the total cost of this technology (EPA, 1980).

2.2.5.3.2. Hydrocyclones

Hydrocyclones use physical method to separate solids from liquids based on the density of the solids to be separated. They are made from metals, plastics or ceramic, and usually have a cylindrical top and a conical base with no moving parts (**Error! Reference source not found.** below). The performance of the hydrocyclone is determined by the angle of its conical section (Colorado School of Mines, 2009). Hydrocyclones can remove particles in the range of 5–15 mm and have been widely used for the treatment of produced water (Colorado School of Mines, 2009). Nearly 8 million barrels per day of produced water can be treated with hydrocyclones (Svarovsky, 1992). They are used in combination with other technologies as a pre-treatment process. They have a long lifespan and do not require chemical use or pre-treatment of feed water. A major disadvantage of this technology is the generation of large slurry of concentrated solid waste.

Figure 2 - Hydrocyclone flow scheme and mode of operation



Source: (Ecologix Environmental Systems, 2010)

2.2.5.3.3. Flotation technology

Flotation technology is widely used for the treatment of conventional oilfield produced water. This process uses fine gas bubbles to separate suspended particles that are not easily separated by sedimentation. When gas is injected into produced water, suspended particulates and oil droplets are attached to the air bubbles as it rises. This results into the formation of foam on the surface of the water which is skimmed off as froth (Igunnu & Chen, 2014).

There are two types of gas flotation technology (dissolved gas flotation and induced gas flotation) based on the method of gas bubble generation and resultant bubble sizes. In dissolved gas floatation units, gas is introduced into the flotation chamber by a vacuum or by creating a pressure drop, but mechanical shear or propellers are used to create bubbles in induced gas flotation units (Igunnu & Chen, 2014). Gas floatation can remove particles as small as 25 mm and can even remove contaminants up to 3 mm in size if coagulation is added as pre-treatment, but it cannot remove soluble oil constituents from water (Colorado School of Mines, 2009).

Flotation is most effective when gas bubbles size is less than oil droplet size and it is expected to work best at low temperature since it involves dissolving gas into water stream. Flotation can be used to remove grease and oil, natural organic matter, volatile organics and small particles from produced water (Igunnu & Chen, 2014) & (Colorado School of Mines, 2009). It does not require chemical use, except coagulation chemicals are added to enhance removal of target contaminants. Solid disposal will be necessary for the sludge generated from this process and the estimated cost for flotation treatment is \$0.60/m3 of produced water (Igunnu & Chen, 2014).

2.2.5.3.4. Evaporation pond

Evaporation pond is an artificial pond that requires a relatively large space of land designed to efficiently evaporate water by solar energy (Colorado School of Mines, 2009). They are designed either to prevent subsurface infiltration of water or the downward migration of water depending on produced water quality (ALL Consulting, 2003).

They are also used to dispose of brine from desalination plants. Mines use ponds to separate ore from water. Evaporation ponds at contaminated sites remove the water from hazardous waste, which greatly reduces its weight and volume and allows the waste to be more easily transported, treated and stored. They can also be used to evaporate the precipitation that falls on a contaminated site. The contaminants that the water picks up on the ground are left behind after it evaporates. This prevents the contamination from spreading further down the watershed. It is a favorable technology for warm and dry climates because of the potential for high evaporation rates. Evaporation ponds are typically economical and have been employed for the treatment of produced water onsite and offsite. Ponds are usually covered with nettings to prevent potential problems to migratory waterfowl caused by contaminants in produced water (Colorado School of Mines, 2009). All water is lost to the environment when using this technology which is major setback when water recovery is an objective for water treatment.

2.2.5.3.5. Adsorption

Adsorption is generally utilized as a polishing step in a treatment process rather than as a standalone technology since adsorbents can be easily overloaded with organics. It has been used to remove manganese, iron, total organic carbon (TOC), BTEX, oil and more than 80% of heavy metals present in produced water (Colorado School of Mines, 2009). There are a variety of adsorbents, such as activated carbon, organoclays, activated alumina and zeolites (Spellman FR, 2003).

Adsorption process is applicable to water treatment irrespective of salinity. It requires a vessel to contain the media and pumps to implement backwashes which happen periodically to remove particulates trapped in the voids of the media. Replacement or regeneration of the media may be required depending on feed water quality and media type. The rate of media usage is one of the main operational costs of adsorption technology (Spellman FR, 2003) & (Colorado School of Mines, 2009). Chemicals are used to regenerate media when all active sites are blocked which often results in liquid waste disposal, and media replacement results in solid waste management.

For adsorption system, mainly the Granular Activated Carbon, in these cases, total cost estimates for GAC systems range from about $l.00/l,000gal ($0.26/1,000 L) for small (1 mgd) systems to about $0.10/l,000 gal ($0.026/1,000 L) for very large systems. Unit costs are highest for small systems with short GAC bed lives and show a steep drop with increasing system size up to about 30 mgd and with increasing bed life up to about six months. Thereafter, unit cost decreases gradually with increases in system size and bed life. (Adams & Clark , 1989)

2.2.5.3.6. Chemical oxidation

Chemical oxidation is an established and reliable technology for the removal of color, odor, COD, BOD, organics and some inorganic compounds from produced water. Chemical oxidation treatment depends on oxidation/reduction reactions occurring together in produced water because free electrons cannot exist in solution (ALL Consulting, 2003). Oxidants commonly used include ozone, peroxide, permanganate, oxygen and chlorine. The oxidant mixes with contaminants and causes them to break down. The oxidation rate of this technology depends on chemical dose, type of the oxidant used, raw water quality and contact time between oxidants and water (Colorado School of Mines, 2009). Chemical cost during this process may be high (AWWA, 1998). Energy consumption accounts for 18% of the total cost of operations and maintenance (Colorado School of Mines, 2009). It requires minimal equipment and has a life expectancy of 10 years or greater and solid separation post-treatment may be employed to remove oxidized particles (Colorado School of Mines, 2009).

2.2.5.3.7. Freeze thaw evaporation

Freeze thaw evaporation (FTEw) process developed in 1992 by Energy & Environmental Research Centre (EERC) and B.C. Technologies Ltd (BCT) is a mature and robust technology for produced water treatment and disposal (Igunnu & Chen, 2014). FTEw process employs freezing, thawing and conventional evaporation for produced water management. Naturally, salts and other dissolved constituents in produced water lower its freezing point below 32 F. When produced water is cooled below 32 F but not below its freezing point, relatively pure ice crystals and an unfrozen solution are formed. The unfrozen solution contains high concentration of dissolved constituents in the produced water and it is drained from the ice. The ice can be collected and melted to obtain clean water.

About 50% of water can be recovered from this process during winter, but at other seasons, no water is recovered because FTEw works as a conventional evaporation pond. FTEw can remove over 90% of heavy metals, TDS, volatile and semi-volatile organics, total suspended solids and total recoverable petroleum hydrocarbons in produced water (Boysen, Harju, Shaw, et al, 1999). FTEw does not require chemicals, infrastructure or supplies that limit its use. It is easy to operate and monitor, and has a life expectancy of 20 years (Colorado School of Mines, 2009). However, it can only work in a climate that has substantial number of days with temperatures below freezing and usually requires a significant amount of land. Waste disposal is essential when using FTE technology because it generates a significant amount of concentrated brine and oil.

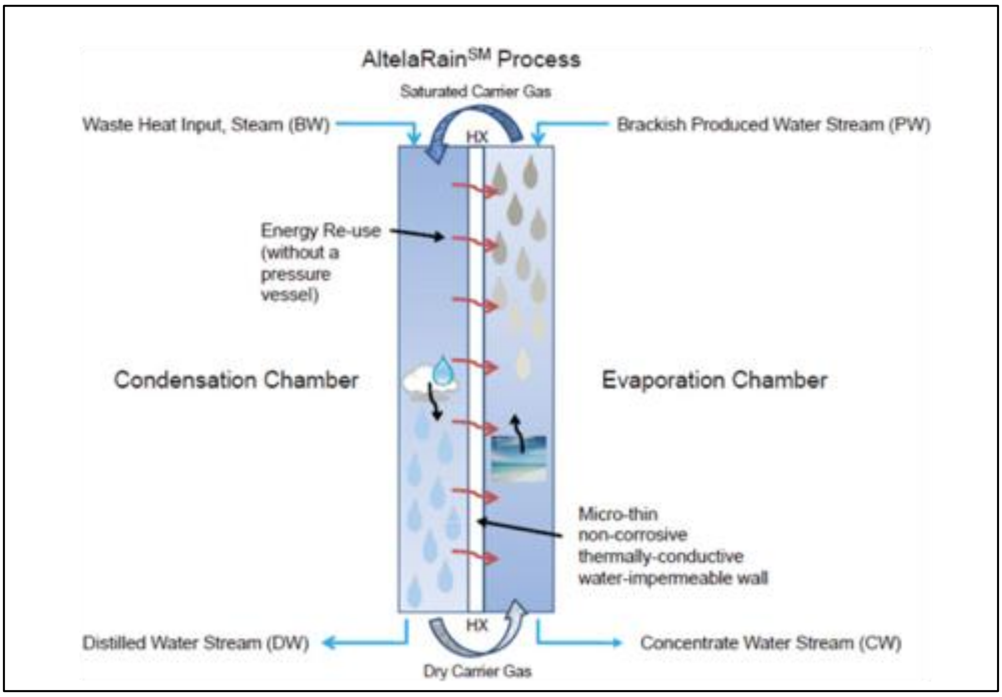
2.2.5.3.8. Dewvaporation: AltelaRainSM process

Dewvaporation is a desalination technology. A prototype system based on dewvaporation process, AltelaRainSM, was developed by Altela Inc. and is already applied in full-scale commercial treatment of produced water. Its principle of operation is based on counter current heat exchange to produce distilled water (Colorado School of Mines, 2009). Feed water is evaporated in one chamber and condenses on the opposite chamber of a heat transfer wall as distilled water (*Figure 3* below).

Approximately 100 bbl/day of produced water with salt concentration in excess of 60 000 mg/l TDS can be processed by this system (Colorado School of Mines, 2009). High removal rates of heavy metals, organics and radionuclides from produced water have also been reported for this technology. In one plant, chloride concentration was reduced from 25 300 to 59 mg/l, TDS from 41 700 to 106 mg/l and benzene concentration from 450 mg/l to nondetectable after treatment with AlterRainSM (Godshall, 2006).

According to Altela Inc., energy requirements of this system are low because it operates at ambient pressures and low temperatures. This makes it a viable alternative water treatment at remote oil wells where there is no high-power grid (Godshall, 2006), but there is no information on the overall cost of the system which is likely to be its major disadvantage.

Figure 3 - Schematic diagram of AltelaRainSM process



Source: (Ecologix Environmental Systems, 2010)

2.2.5.3.9. Macro-porous polymer extraction (MPPE)

Macro-porous polymer extraction (MPPE) is one of the best available technologies and best environmental practices for produced water management on offshore oil and gas platforms (Akzo Nobel MPP Systems, 2004). It is a liquid–liquid extraction technology where the extraction liquid is immobilized in the macro-porous polymer particles. These particles have a diameter of 1000 mm, pore sizes of 0.1–10 mm and porosity of 60–70%. Polymers were initially designed for absorbing oil from water but later applied to produced water treatment in 1991 (Meijer & Madin, 2010). In 2002, commercial MPPE was used for the removal of dissolved and dispersed hydrocarbons, achieving 99% removal of BTEX, PAHs and aliphatic hydrocarbons at 300–800 ppm influent concentration. It was also reported that removal efficiency of 95–99% for aliphatics below C20 and total aliphatic removal efficiency of 91–95% was possible (Pars & Meijer , 1998).

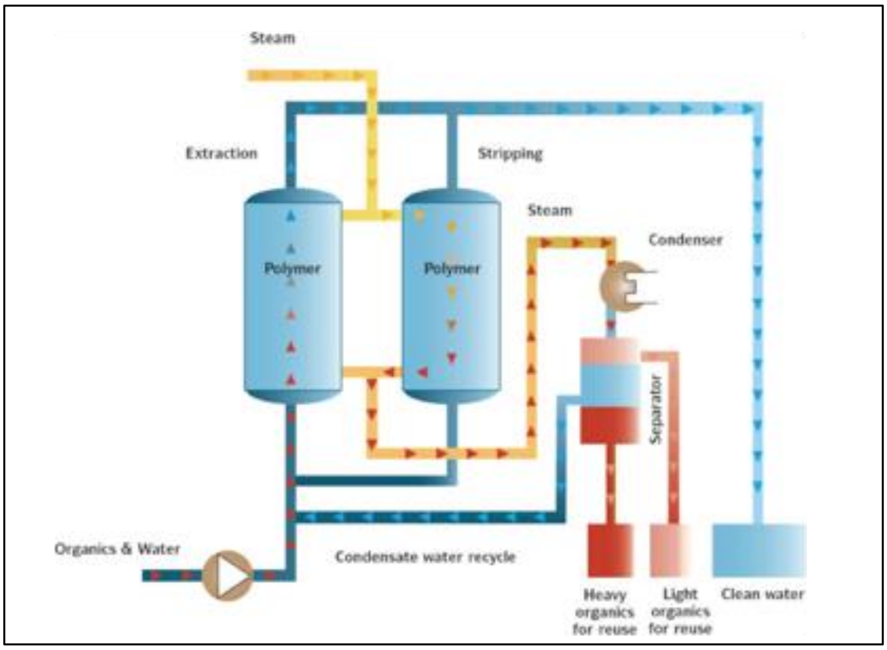
In the MPPE unit, produced water is passed through a column packed with MPPE particles containing specific extraction liquid. The immobilized extraction liquid removes hydrocarbons from the produced water as shown in *Figure 4*. The two columns allow for continuous operation with simultaneous extraction and regeneration (Akzo Nobel MPP Systems, 2004). Almost all hydrocarbons present in produced water can be recovered from this process which can in turn be disposed or recycled. Stripped hydrocarbons can be condensed and separated from feed water by gravity, and product water is either discharged or reused.

This technology is essentially used to reduce the toxic content of produced water and can withstand produced water containing salt, methanol, glycols, corrosion inhibitors, scale inhibitors, H2S scavengers, demulsifies, defoamers and dissolved heavy metals. Pre-treatment through hydrocyclones or other flotation methods is however necessary before letting produce water from oilfields flow into the MPPE unit. Studies have shown that in gas/condensate produced water streams pre-treatment is not required and MPPE can remove the whole spectrum of aliphatics, as well as BTEX and PAHs (Igunnu & Chen, 2014).

For more details in term of comparison of applicability, efficiency, advantages, disadvantages, cost of the above-described technologies, can found resumed on ***Table 26*** and ***Table 27*** available one appendices page.

As international legislations seek ‘zero discharge’ of contaminants into the environment and focus on the EIF of contaminants, MPPE will be a major produced water treatment technology in the future. A study carried out by Statoil to compare the effect of different treatment technologies of oilfield produced water on EIF found that the MPPE technology had the highest EIF reduction of 84% (Igunnu & Chen, 2014). A relatively high cost of unit is a major disadvantage of this technology. The ***Table 26*** and ***Table 27*** in appendices page, show a comparison of produced water treatment technologies discussed in this section

Figure 4 - Macro-porous polymer extraction (MPPE)



Source: (Ecologix Environmental Systems, 2010)

The chosen technology that would be suitable to treat produced water form SPT, it will depend on the contaminants to be removed, the final destination to be given to the treated PW and it can be done with the following objectives: removal of oil in dispersed forms; removal of soluble organic compounds; disinfection, to remove bacteria; removal of suspended solids, turbidity; removal of dissolved gases, such as light hydrocarbon gases, CO2 and H2S; desalination, to remove dissolved salts, sulfates, nitrates and scale agents; softening, to remove excess hardness; and adjustment of the sodium adsorption ratio (Arthur, Langhus, & Patel, 2005). Hydrocyclones, flotators, membrane filtration, thermal treatment, adsorption, conventional gravity separators and gravitational plate separators are some of the most used technologies.

2.3. Ranking Treatment Technology

The effectiveness and performance of the various treatment technologies can also be analyzed according to a new five-step ranking approach devised by the authors and described in this section. Rankings can best be used to select between technologies based on a carefully defined set of criteria. Rankings will need to be updated as commercialized technologies will change and as innovations are installed and made newly available. The ranking of each step depends on the rankings of other steps.

Reasonable engineering judgment and experience assists in utilizing this ranking criterion. The following is an example of a ranking scheme for treatment technologies as they apply to the treatment and management of produced water. It should be noted that the rankings that follow are subjective, are the product of the authors, and are subject to change.

Note: Each ranking step described in this section is based on (Arthur, Langhus, & Patel, 2005), and for better explanation and understanding, the ranking process we will use Reverse Osmosis (RO) treatment technology as an example.

Step 1 – Ability to remove technology specific contaminants:

The simplest method to express the performance of a treatment technology is the removal of contaminants. Ranking can be assigned in five categories (see below *Table 3*):

Table 3 - Ranking the ability of technology remove specific contaminants.

Removal of contaminants, %	Rank
>95	5
90-95	4
75-90	3
50-75	2
< 50	1

Source: (Arthur, Langhus, & Patel, 2005)

This technology has ability to remove dissolved salts between 75-90%, which normally Ranks [rank 3]

Step 2 – Consumption of resources to achieve desire removal using given technologies:

The consumption of resources in terms of effort, cost, energy, natural resources, etc. must be considered in ranking. Regarding the interdependency of ranking criteria, in the case of RO operation, higher pressure across the membrane (energy) is required to achieve higher removal of salts at higher recovery rate. Find below *Table 4* of ranking process:

Table 4 - Ranking the ability of technologies consume cost, energy and material to run.

Level of resources consumption	**Rank**
Low	5
Moderately low	4
Moderate	3
High	2
Veri High	1

Source: (Arthur, Langhus, & Patel, 2005)

The RO technology has ability to remove dissolved salts 75-90%, which normally Ranks 3 and for that. In term of resources, it would need a moderated level of resource (**cost, energy and material)** consumption to run, ranking 3. For the same membrane, with capacity for removal of contaminants at level >95% [rank 5], the removal requires technology requires high energy [rank 2].

Step 3 – Requirement of pre- or post-treatment technologies with given technologies:

Most of the treatment technologies require pre- or post-treatments to improve efficiency, to achieve better quality, to handle byproducts, etc. The extent of such requirements significantly contributes to the overall performance but also adds to cost, facilities, and technological complexity. Ranking assigned in five categories shown in below *Table 5*:

Table 5 - Ranking the ability of technologies require pre or post treatment

Pre/Post treatment requirement	Rank
Basic: cooling, heating, settling, impoundment, etc.	5
Primary: pH adjustment, softening, chemical addition, de-oiling, suspended solid removal, sand filtration, etc. + technologies in previous section	4
Secondary: soluble hydrocarbons removal, GAC, dissolved gas removal, biological treatments, disinfection, etc. + technologies in previous sections	3
Moderate: regeneration, fouling prevention, trickling filter, constructed wetland, ionization and removal, UF or NF, low pressure RO, etc. + technologies in previous sections	2
Significant: high pressure filtration, high pressure RO, NORM treatment, etc. + technologies in previous sections	1

Source: (Arthur, Langhus, & Patel, 2005)

Step 4 – Durability of the treatment technology:

Some technologies rely on automated activation of pumps and valves to move fluid while other technologies feature simpler flow paths that are gravity-driven. Simpler technologies are easier to maintain and cheaper to operate. This factor analyzes the degree of durability within a technology. Find more details on *Table 6* below.

Table 6 - Ranking durability and complexity of the technologies

Durability Factor	Rank
Inlet water driven by gravity, no moving parts, facility not prone to fouling and scaling, maintenance by schedule or automated warning	4
Simple automated pumping cycles and few adjustments needed	3
Complex automated cycles needing occasional adjustment and repair.	2
Operator onsite at all times makes adjustments and repairs during process.	1

Source: (Arthur, Langhus, & Patel, 2005)

Step 5 – Mobility of the treatment units:

The compatibility of treatment technologies to be performed as mobile units benefits the produced water treatment and adds flexibility during oil and gas operations. If the treatment units are self-contained and mobile, the operator can change locations as water production changes within the field. Many of the individual technologies can be performed by mobile units. However, they may require pre- or post-treatments which can only be performed by fixed units. Such operations are categorized as partially mobile treatments in the following ranking and others can be Fully mobile or fixed, as presented on *Table 7* below;

Table 7 - Ranking the mobility of treatment technologies

Mobility of treatment technologies	Rank
Fully mobile	2
Partially mobile	1.5
Fixed	1

Source: (Arthur, Langhus, & Patel, 2005)

Good quality produced water from oil or gas formations may require minimum polishing treatments which can be accomplished by compact modules of GAC and RO operated on a mobile treatment truck. Such treatments are fully mobile [rank 2].

Step 6 – Level of contaminants in influent produced water:

The quality of influent produced water also contributes to the overall performance of treatment technologies. This can be ranked as show on below *Table 8*:

Table 8 - Ranking the level of contaminant removal after treatment

Level of contaminants	Rank
Low: suspended solids, moderate concentration of free or dispersed oil, low hardness level, easily removable gases etc. TDS: < 5,000 ppm TOC, TPH: < 30 ppm	5
Medium: ammonia, boron, hardness ions, BTEX, dissolved gases, fine oil particles, metal ions etc. TDS: 5,000-10,000 ppm TOC, TPH: >30 100 ppm + contaminants in next section	4
High: hydrogen sulfide, heavy metals, weak ions, NORM, monovalent salts, trace soluble organics etc. TDS > 10,000-35,000 ppm TOC, TPH > 100 ppm + contaminants in next sections	3

Source: (Arthur, Langhus, & Patel, 2005)

Final Step – Calculation of overall rank based on above ranking criteria:

After estimating ranks of each five steps, the final formula as described below calculates overall rank. The possible highest rank is 7 and the least possible rank is 1. On the scale of 7, the treatment technologies with higher rank confirm better performance, economics and flexibility. The overall ranking (OR) equation is:

Equation 1 - Equation for calculation of overall rank (OR)

$$OR = \frac{(STEP\ 1 + STEP\ 2 + STEP\ 3 + STEP\ 4 + STEP\ 5)}{STEP\ 6}$$

Source: (Arthur, Langhus, & Patel, 2005)

2.4. Corrosion Inhibitor and biocide

Metals present in the PW (in dissolved or in micro particulate form) can be Iron, nickel, lead, copper, zinc, manganese, chromium, barium, mercury etc. (Aphane, 2007) and some these metals can precipitate by exposition to the atmosphere. Chemical additives are chemicals that are added in wells during drilling, fracturing and operation, such as biocides, corrosion inhibitors, scale inhibitors, and emulsion breakers (Shittu, 2008).

Most of these chemicals, the biocide and inhibitor, are soluble in water. Radium-226 and Radium-228 are the most naturally occurring radioactive materials. Radium is derived from uranium and thorium. Suspended solids are result of formation of solids, bacteria, waxes, sand, silt etc. Few organisms survive in PW due to its toxic nature. These solids can corrode equipment and pipes. O2, CO2, and H2S are some of the common gases that are dissolved in PW (Veil et al, 2007).

Inhibitors are chemicals that are used to protect the surface of metals used in oil and gas industries to prevent corrosion. They protect the surface of metals either by merging with them or by reacting with the impurities in the environment that may cause pollution (Rajeev , Surendranathan, & Murthy , 2012)

Biocides[12] are also known as disinfectants, preservatives, sterile and, anti-microbial agents and antiseptics.

2.4.1. Use of Inhibitor and biocide

The biocide, due to its characteristics, kills any living cells with depending on the living characteristics and upon on several variables not least of which is the dose (the concentration of biocide) and the time it is in contact with microorganisms. Most biocides can also be regarded as biostatic. That is, at concentrations lower than that required to kill, the biocide inhibits cell growth, whilst it is present. Once the chemical is removed, the bacteria will continue to grow again. At doses lower than biostatic, the biocide can become source of nutrition & therefore encourage growth.

In oilfield operations, it is usually necessary to dose the system, either periodically or continuously, with biocides that prevent microorganisms growing or kill them outright. The

[12] http://www.oilfieldwiki.com/wiki/Biocide

most common non-oxidizing organic biocides in the oilfield are glutaraldehyde (glut) and tetrakis-hydroxymethyl-phosphonium (THPS), with smaller amounts of formaldehyde and acrolein being used.

Sasol, uses clay swelling inhibitor chemical such us XLAmine in produced water re-injection process. The XLAmine is pumped into the PW stream at PW injection pump suction in dosage between 50-3000ppm, depending on research and water conditions. In addition to the requirement to reduce clay swelling around the well bore, it is necessary to insure that, the bacterial inhibitor, the biocide, is injected at the mid-point along the flowline and at the wellhead itself (around 200ppm injection rate in each case).

The effectiveness of the bacterial inhibitor should be checked at each injection event, and the inhibitor changed periodically when any buildup of bacterial immunity is observed.

2.4.2. Hazards and environmental risks of Biocide

Because biocides are intended to kill living organisms, many biocidal products pose significant risk to human health and welfare. Great care is required when handling biocides and appropriate protective clothing and equipment should be used.

The use of biocides can also have significant adverse effects on the natural environment. Anti-fouling paints, especially those utilizing organic tin compounds such as TBT, have been shown to have severe and long-lasting impacts on marine eco-systems and such materials are now banned in many countries for commercial and recreational vessels. Disposal of used or unwanted biocides must be undertaken carefully to avoid serious and potentially long-lasting damage to the environment.[13]

2.5. Matrix Leopold

According to Sánchez, (2013), the Leopold Matrix tool is a matrix format designed to assess environmental impacts. The matrix is composed of the intersection of squares environmental impacts resulting from each activity. Between 1 and 10 are indicated, corresponding respectively to the magnitude and importance of the impact. Number 1 corresponds to the condition of least magnitude (minimum of potential environmental change) and of minor importance (minimum significance of the action over the environmental component considered). To the number 10 correspond the maximum values of these attributes. The (+) or (-) sign in front of the numbers indicates whether the impact is beneficial or adverse,

[13] http://www.oilfieldwiki.com/wiki/Biocide#Hazards_and_environmental_risks

respectively. As in other methods, there is the risk of subjectivity. Impacts have two main attributes: magnitude (scale magnitude of the interaction of actions) and importance (intensity of effect in the area of influence of the enterprise or outside it, corresponding to the environmental factor). "Magnitude is the extensive measure, degree or scale of impact. Importance refers to the significance of the cause over the effect (Richieri, 2006).

As pointed out by Fogliatti et al., (as cited in Cavalcante & Leite, 2016), the advantages of this tool are in allowing easy understanding and address biophysical and social factors. It also allows us to use little data in its elaboration, qualitative and quantitative. It has a multidisciplinary character, low cost and simplicity in the elaboration, presenting good orientation and visual disposition.

CHAPTER III

3.0. METHODOLOGY

The present study is a case study, descriptive, with a qualitative approach. According to Yin (2009) & Eisenhardt (1989), the case study is a research method that generally uses qualitative data, collected from real events, with the objective of explaining, exploring or describing current phenomena inserted in their own context. The study covered all Gas Production Process from Central Processing Facilities for Sasol Petroleum Temane, from the capture of natural gas raw material to the discharging process of PW into the reinjection well.

Based on the objectives the research the methodology applied for the research was fragmented into four (4) parts. The first stage concerns the elaboration of the theoretical framework about natural gas processing, produced water and technologies for PW treatments. The second stage was focused on the characterization of the Sasol Gas Production Process and the separation natural form of the produced water. The third stage was focused on produced water sampling and analysis, as well as evaluation of the quality of the parameters compared to that established in the law, regulation and environmental protection standards established by IFC, MICOA and FAO. Based on the results obtained in the previous phase, were identified set of technologies for produced water treatment that could be implemented to Sasol Petroleum Temane CPF, to reduce the negative impacts of PW in equipment and the environment. Each step of the methodology presented above is described in further detail below.

3.1. Sampling and data analysis

The data collection was based observation of entire gas production process combined with review of company production procedures which show how the production process occurs. In order to evaluate the quality of produced water, the SPT Central Processing Facilities laboratory team collected ten (10) samples of produced water in 5 (five) different days (see table below). From these ten samples: five (5) samples were collected before injection of corrosion inhibitor (SB1 to SB5) at the first **PW Tank Storage (DM-9102)** and five (5) samples were collected before after (SA1 to SA5) were before injection of corrosion inhibitor at **Rejection well (#T23)**, as shown in below ***Table 9***, below.

Table 9 - Sasol PW sample identification

Date of sample	Before corrosion inhibitor at PW Tank Storage (DM-9102)	After corrosion inhibitor at Rejection well #T23	Total sample
26/02/2020	SB1	SA1	2
02/03/2020	SB2	SA2	2
04/03/2020	SB3	SA3	2
16/03/2020	SB4	SA4	2
18/03/2020	SB5	SA5	2
			10

Source: Autor (2020)

These produced water after its collection, were analyzed by Temane's Laboratory team in the central processing facilities. The ***Table 10*** shows the detailed parameters, which were performed analyses for the characterization of the samples under study.

Table 10 - Parameter analyzed on Sasol PW sample

Parmenter		
Physicochemical	**Metal**	**Organic (hydrocarbon)**
PH	Fe	Benzene
TSS		Toluene
Conductivity		Xylene
TDS		
TEG		
Density		
Temperature		
Salinity		
Chlorides		
Bacteria count		

Source: Autor (2020)

The analysis and characterization of samples used by the Sasol laboratory team were performed according to standardized methods, to ensure the desirable characteristics quality, safety, reliability, efficiency of the results. The standard methodologies used for the analyses of the desired parameters are shown below.

The method used for pH testing was APHA 4500-H+ B (Electrometric). The method used for Conductivity testing was APHA 2510 B (Conductivity Meter). According to EPA, (2001), the conductivity is mostly related to dissolved solids content in the water. When the TDS is not known, we use the value of conductivity parameter to estimate the TDS through an algorithm. For this research we used the following: Total Dissolved Solids (mg/l) = Conductivity (µS/cm) x 2/3. This formula is mostly used to convert de conductivity to TDS for many surface waters, when there is no TSD data available.

The metal determination method was based on the fundamentals of optical absorption spectrometry with inductively coupled plasma, based on the USEPA 6010 method. To determine BTEX (Benzene, Toluene and Xylene) or organic element (hydrocarbon), the test method used was USEPA 8021B, which was based on the gas chromatography (CG) technique. Salinity which is generally expressed in terms of sodium chloride (NaCl) equivalent in milligram per liter (mg/L) or partly per million (ppm) was determined on the basis of the APHA 2520B testing method.

Suspended solids (SS) correspond to the part of the solids that are suspended in the liquid and cause the turbidity of the water. The proposed method for SS analysis is based on APHA 2540, using the UV-visible spectrophotometry analytical technique that allows determining the concentration of a compound in solution. The temperature was measure by a thermometer. The bacteria count and density measurement was used Membrane Filtration, based EPA Method 1103 and for Triethylene glycol (TEG) present in PW was used gas chromatography.

Due to the administrative and safety procedures of Sasol Petroleum Temane's interns, the entire sampling and laboratory analysis process were carried out by specialized and qualified laboratory technicians form Sasol staff.

3.2. Methodologic process

3.2.1. Quality evaluation of PW

The methodologic process consisted first on interpretation of the result of the analyzed parameter by comparing the results of the samples with established limits for several parameters as criteria for quality classification. Among the Mozambican and other worldwide norms and regulations related to water resources, three norm and regulation such as (1) Environment Protection (Standards for effluent discharge) Regulations 2003 (G.N. No. 44 of 2003), published by FAO (2013), (2) Quality Standards Regulation: Environmental and Effluent Emission from Mozambique published by MICOA (2004) and (3) Standards for Emissions, Effluent and Waste Levels from Onshore Oil and Gas Development published by IFC (2007), all of them establish similar limits for several parameters as criteria for quality classification. These resolutions and norms, as well as includes limits and criteria of physicochemical, organic and metal parameters, establishes the maintenance of good practices and perform studies in order to remove and control all the contaminates. Each presented parameter present on the produced water has its own limit range of classification, and each range determine whether the parameter in represent good or bad water quality.

3.2.2. Evaluation of environmental impact of PW

The second stage of the work consisted in identifying the significance of impacts that the produced water can cause to the CPF's equipment when it flows in the pipeline and environmental when they are launched or buy accident gets to the receiving body without previous treatment. Before determining the impact significance, each parameter previously found were evaluated by classifying them based on the maximum and minimum emission limit determined by the standards and regulations, mainly, the Quality Standards Regulation for Environmental and Effluent Emission of Mozambique published by MICOA and Standards for Emissions, Effluent and Waste Levels from Onshore Oil and Gas Development published by IFC. Then significance of each parameter is evaluate based on Leopold Matrix, which allows to associate the impacts resulting from a given source of pollution with the various environmental characteristics of its area of influence, such as Physical environment (water and soil), equipment and entire Sasol facility.

3.2.3. Evaluation of effectiveness and efficiency of Corrosion inhibitor

The SPT uses a corrosion inhibitor in order to decrease the corrosion rate of metal (CPF pipeline),[14] in presence of water and other elements that influence increasingly the corrosion of equipment of CPF without significantly changing the concentration of any corrosive agent. Therefore, at third stage is evaluated the efficiency of corrosion inhibiting agents used in SPT, and their influence on reducing corrosion in the pipes. This evaluation was basically made by comparing the data results (parameter) of produced water before and after application of corrosion inhibitor and results was presented in percentage of increasing and reduction of each parameter presented in produced water. This evaluation allowed to find how the corrosion inhibitor was or not effective, how it affected the PW characteristic change.

With the significance of impact found and inefficiency of corrosion inhibitor helped a lot to validate the possibility of designing suitable system for PW water treatment in SPT's Central Processing Facilities in Temane in to reduce, remove and control contaminants present into the PW.

3.2.4. Treatment Technology Cost Estimation

The fourth stage consisted of selection of a suitable technology, among several methods and technologies, capable to treat or clean the produced form impurities and to reduce the as

[14] Corrosion inhibitor is a "chemical substance that when present in the corrosion system at a suitable concentration decreases the corrosion rate, without significantly changing the concentration of any corrosive agent." It is generally effective in small concentrations.

much as possible the corrosion impact to the Central Processing Facilities equipment and reduce the possibility of impact negatively the receiving body – environment: soli, water and surrounding peoples. To find a suitable technology, each selected technology, passed throw a of calculation and analysis de investment cost for designing, installation, operation and possibility of maintenance.

3.2.5. Evaluation of suitable technologies by ranking process[15]

To find a suitable technology it was needed to evaluate among set of technology, the best ones that would have sustainable cost, would treat very well de produced water and would be efficient and effective. To evaluate the effectiveness and performance of the various treatment technologies, were used can a **Ranking process** based on (Arthur, Langhus, & Patel, 2005). This Ranking process analyzed de performance of different technologies of water treatment according to a new five-step ranking approach. The Rankings were used to select between technologies based on a carefully defined set of criteria.

Therefore, to find a suitable, feasibility and efficiency of treatment technology for STP Central processing facility, there were used Overall Ranking (OR) below formula (2), based on (Arthur, Langhus, & Patel, 2005).

$$\mathrm{OR} = \frac{\mathrm{STEP\ 1 + STEP\ 2 + STEP\ 3 + STEP\ 4 + STEP\ 5}}{\mathrm{STEP\ 6}}$$

Source: (Arthur, Langhus, & Patel, 2005)

Were:

Step 1: Comprise to the ability of treatment technology to remove specific contaminants, in percentage. Ranking can be assigned in five categories: 1 = capacity to remove contaminant < 50% and 5 = capacity to remove contaminate >95%,

Step 2: Comprise on capacity of consumption of resources in terms of effort, cost, energy, natural resources to achieve desired removal using given technologies. It can be ranked in five categories where 1= very high and 5 = low.

Step 3: Comprise on requirement of a given technologies to use pre- or post-treatment technologies. Ranking assigned in five categories: 1= high and significant needs of pre

[15] More detail about the Ranking Treatment Technology is available on subchapter 2.3 on literature review or you find on (Arthur, Langhus, & Patel, 2005), available on internet: https://www.researchgate.net/publication/267836025_Technical_Summary_of_Oil_Gas_Produced_Water_Treatment_Technologies

and post treatment and 5 = lower and basics needs of pre and post treatment technologies.

Step 4: Comprise on what is durability of the treatment technology. This factor analyses the degree of durability within a technology. It can be ranked 4 four categories: 1 = technologies that need to maintain all the time and have too much moving parts and 4 = technologies with less of moving part, simple and less maintenance are needed.

Step 5: Mobility of the treatment units. If the treatment units are self-contained and mobile, the operator can change locations as water production changes within the field. Such operations are categorized as partially mobile treatments in the following ranking: 1: Fixed, 1,5: Partially Mobile and 2: Fully mobile.

Step 6: Level of contaminants in influent produced water. The quality of influent produced water also contributes to the overall performance of treatment technologies. This can be ranked for 3 to 5 as shown: 3: represent high quantity of contaminant in water, 4: average or medium and 5: low contaminant.

After estimating ranks of each five steps and calculated the overall rank using the final formula (2) above, is evaluated the performance of the technologies. The possible highest rank is 7 and the least possible rank is 1. On the scale of 7, the treatment technologies with higher rank confirm better performance, economics, and flexibility. This result is also compared with the previously estimated cost of investment and operation calculated.

Compare the results form process 2 and chose and propose a suitable method based on Step 1, 2 and 3, which is more effective and efficient, which spend less cost and bring better results.

CHAPTER IV

4.0. RESULTS AND DISCUSSION

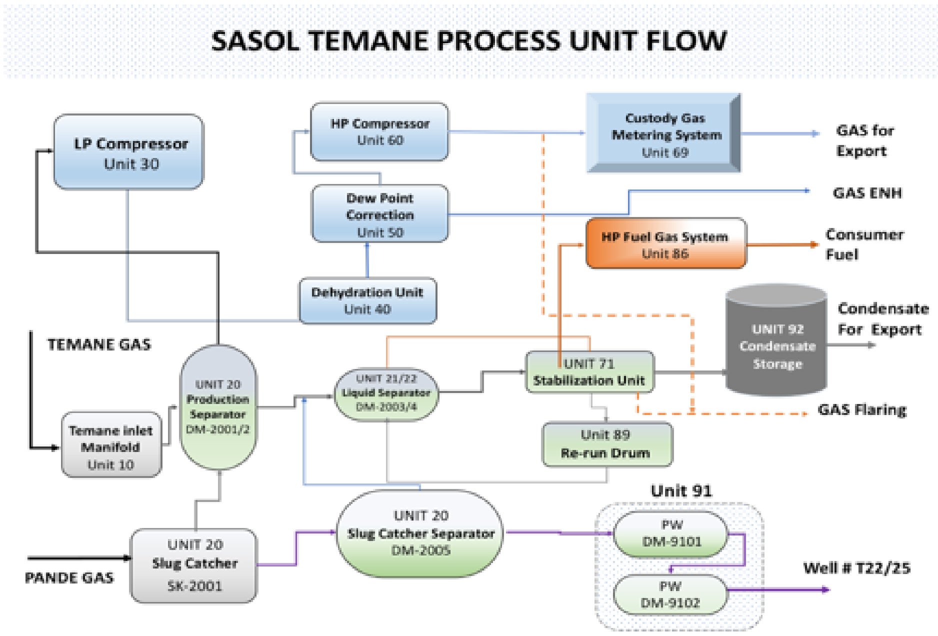
To achieve the key objective of the research, of finding and propose a suitable method of treatment of Produced Water (PW) at SPT Central Processing Facility, there were made some observation at entire gas production process combined by a collection of ten water samples, five of them collected before the injection of the corrosion inhibitor in the first PW Tank Storage and other five collected before corrosion inhibitor injection in the rejection well. Later these samples went through a physical, chemical, and organic laboratory analysis at Sasol Laboratory. The analysis and characterization of samples were performed with specialized laboratory team by using standardized methods such as APHA, USEPA and EPA, to ensure the desirable characteristics quality, safety, reliability, efficiency of the results.

From laboratory analyses made on the ten samples of water produced, in this chapter we compared the values of the samples with the with what is established by the law, regulation and environmental protection standards such as IFC, MICOA and FAO. From the results obtained, set of produced water treatment technologies were selected to be implemented on Sasol Central Processing Facility (CPT), through a calculation by using Ranking process based on (Arthur, Langhus, & Patel, 2005), to reduce and control the levels of contaminants in water before reinjecting into the well and reduce corrosion levels in the equipment. To find a suitable technology, each selected technology, passed through a estimation and analysis de investment cost for designing, installation, operation and possibility of maintenance.

4.1. Description of Gas Process and Produced Water Generation

The produced water that is studied in the present research is resulting from raw natural gas processing from Temane and Pande wells in Inhambane. The processing activity is carried out by the Sasol Petroleum Temane Company (SPT) by means of a natural gas Central Processing Facility (CPT), which is located at Temane, in the Inhambane Province, where the main product, the methane gas (lighter hydrocarbon), is separated from condensate (a mixture of low-density hydrocarbon) and the Produced Water. To get set of these products, Sasol's Central Processing Facility (CPT) goes through eight (8) phases, shown in **Figure *5*** and shortly described below.

Figure 5 - Sasol Temane Process Unit Flow



Source: Autor (2020)

The natural gas from Pande and Temane comes from twelve (12) remotely located gas wells at low pressure of 20 bar instead of required 60 bar run the system. Most of the gas available in the wells are associated with mixture liquid called slug, composed with condensate (wet gas) and water, when in factory, the liquid can over flood the system and leads to a formation of hydrates that normally create a corrosion to the utilities, which might cause damage to the pipeline and equipment. In order to avoid flood the system, the slag is sent to a separator called Slag Catcher (SK-2001), which separate the liquids and gas from the mixture. It first, goes to the slug catcher, where the liquids (water and condensate) are removed by gravity and send to the second Slug Catcher Separator-DM2005 and next routed to the Liquid Separators (DM-2003 and DM-2004) where Produced Water is separated from Condensate by density difference at environment temperature for 25°-30°C and pressure of 30 bars. The heavier water portion (removed from the gas) is then collected and routed to the Produced Water Storage Tank (DM-9102 or DM-9101). Simultaneously, while condensates and water, are send to liquid separator, the raw natural gas of Pande, that comes from slug catcher, goes together with the gas coming from Temane source to the Production Separator (DM2001 and DM2002).

The raw natural gas comes from the wells at low pressure of 20 bar because of the decline of gas pressure at the reservoirs. So, the to run the SPT pressure to 60 bar, as recommended, the gas is routed to the LPC, Low Pressure Compressors (Unit 30's), to increase the pressure of the gas from 20 bar to 60 bar, in order to run in the system for feather process.

After that, the gas is sent to the gas dehydration unit (unit 40's) to remove moisture available in the gas by using Tri-ethylene glycol (TEG) – with hygroscopic nature, to prevent gas condensation. The Triethylene glycol is heated to a high temperature and put through a condensing system, which removes the water as waste and reclaims the TEG for continuous reuse within the system.

The natural gas and any additional components present, due to certain low temperature, for a given pressure, will start to condense out of at the gaseous. Therefore, the outlet gas for unit 40 goes to the Dew point Correction unit, to correct the dew point of the gas as way to avoid condensation of the gas when it is sent to our consumers (ENH and South Africa). The correction is done by chilling the gas using liquid propane and the heavier hydrocarbons condense and are separated from the lighter ones. Some of the dew point corrected gas exported to ENH while the remaining is routed to the High-Pressure Compressors (HPC) - Unit 60's, with a purpose of increase the gas pressure to 125 bar, to ensure that the end gas product sent through a pipeline has enough pressure to reaches our consumers in South Africa. From the HPC's, the gas is sent to the Custody Metering to analyze the quality of the gas (gas composition, the dew point, the moisture content, temperature, pressure, specific gravity and the heat value of the gas) as required to consumers is on specifications.

Part of the condensate (free of water) with temperature in between 25°-30°C and pressure of 30 bar is routed to the Condensate Stabilization Unit to remove the vapor or Off gas (C_1 to C_4) and heated to produce energy for the company. The main reason of stabilizing the condensate is to control gas stabilization and ensure that it is stored and transported safely and avoid accidents during transportation, as the condensate are naturally more volatile.

The produced water that that goes to first PW drum DM9101 might come with small amount, around 10%, of condensate. To remove this condensate, the 90% of the PW is sent to the second PW drum DM9102 while the 10% remain in first drum. The PW from drum DM9102 is re-injected or well drilled into a dedicated injection wells (T#23) and completed in a containment section of the reservoir which has no possibility of communication with the gas zones or the water table. As the produced water is re-injected into the well, the oxygen is excluded from the water to avoid the precipitation of hydroxides and the formation of sulphate reducing bacteria (SRB's), as this may cause souring of the reservoir and significantly affect permeability.

To avoid reservoir pore space blockage, SPT, uses clay swelling inhibitor chemical such us XLAmine in produced water re-injection process. The XLAmine is pumped into the PW stream at PW injection pump suction in dosage between 50-3000ppm, depending on research and water conditions. In addition to the requirement to reduce clay swelling around the well bore, the bacterial inhibitor, the biocide, is injected at the mid-point along the flowline and at the wellhead itself (around 200ppm injection rate in each case).

4.2. Composition and Characterization of the Produced Water

Based on the results obtained through physicochemical, metal and organics samples before corrosion inhibitor injection (S1 and S2) and after corrosion inhibitor injection (S3 and S4), can be addressed about the parameters presented in ***Table 11*** below. Is important to highlight that the parameters discussed in this subchapter are results of sampling, collection and laboratory analysis of water samples carried out entirely by the Sasol laboratory team.

Table 11 - Typical Parameter of Sasol PW samples Vs the regulation limits

Parameter	Before inhibitor reinjection					After Inhibitor reinjection					Regulated limit
	SB1	SB2	SB3	SB4	SB5	SA1	SA2	SA3	SA4	SA5	Maximum
Physicochemical											
TSS (mg/L)	176	84	208	36	114	168	160	28	38	42	50
TDS (mg/L)	8655.7	8591.7	11141	7672.6	7566.2	9202.1	7302.3	10359	7843.2	7879.2	650 - 1675
Conductivity (µS/cm)	12919	12823.4	16628.4	11451.7	11292.9	13734.5	10899	15461.2	11706.2	11760	1000 - 2500
TEG (mg/L)	1565	4030	2566	8973	4993	2585	1903	NA	NA	1402	20-39.4
Salinity (mg/L)	7500	7500	9900	6600	6500	800	6300	9200	6800	68000	~$4*10^6$
Chlorides (mg/L)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	600 - 1200
Bacteria count (bact./L)	$1x10^4$	1 $x10^6$	1 $x10^6$	1 $x10^6$	1 $x10^6$	100	100	1000	1000	1000	1000
Density (mg/L)	1003900	1003800	1005600	1003600	1002600	1003900	1003800	1004700	1003200	1001700	1020000
pH	5.31	5.06	5.44	4.8	4.77	5.31	4.9	5.23	4.73	4.73	6 - 9
Temperature	20	20	20	20	20	20	20	20	20	20	~ 40
Metal											
Iron (mg/L)	10.17	9.33	10.4	10.3	10.3	8.63	10.64	9.84	9.55	9.55	< 5
Organic											
Total hydrocarbon (mg/L)	169.1	203.3	910.5	1499	1452	347	976.8	915.1	0	1170	10

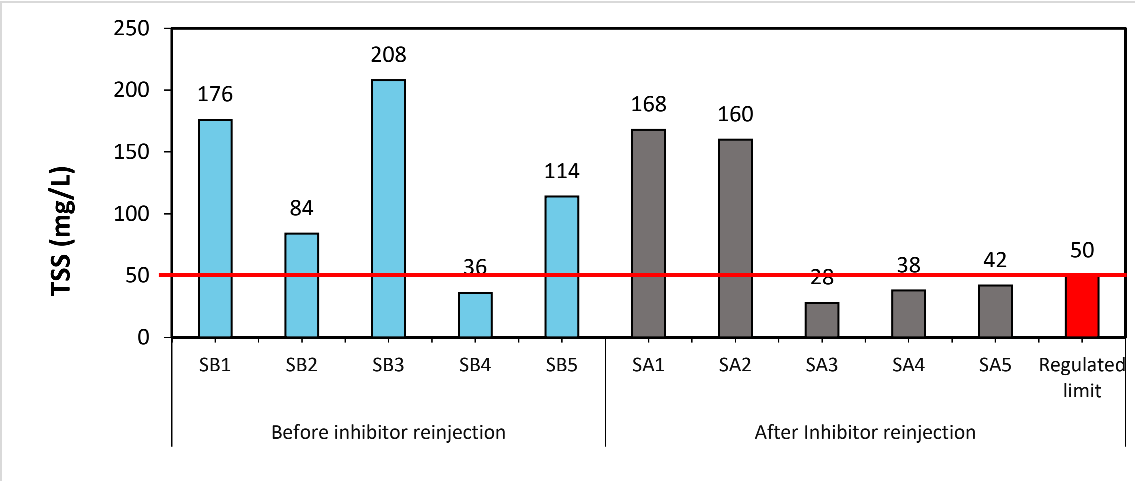
Source: Sasol Laboratory Analyses Report (2020)

4.2.1. Physicochemical analysis

4.2.1.1. Total Suspended Solids (TSS)

Investigation made from PW sample data and comparison to MICOA legislation and IFC standard, shows that total suspended solids (TSS), present higher values around 80 to 210 mg/L, in comparison to the established on standards (50mg/L), as presented on ***Table 11*** and ***Graphic 1*** below.

Graphic 1 - TSS produced water results vs the regulation limits



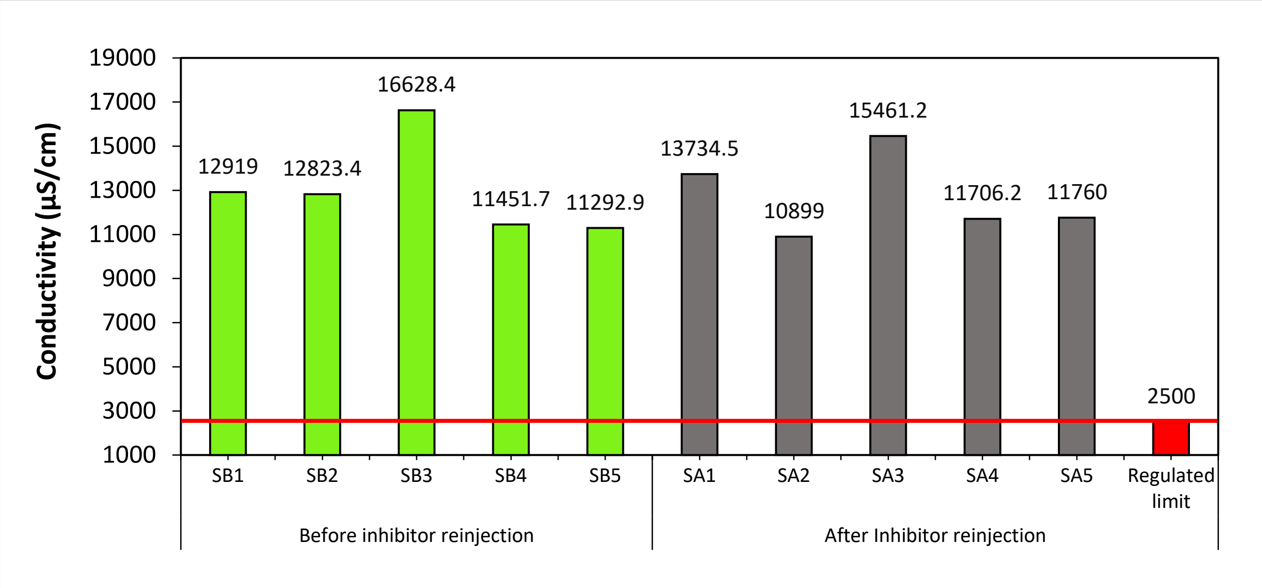
Source: Autor

The sample collected and analyzed after the reinjection of corrosion inhibitor in PW, has shown a considerable change and reduced the amount on contaminants below the almost the 50 mg/l established, even though it didn't meet the standard, due to high presence of turbidity, represented of solid elements, such as oil, condensate and other particle that cannot dissolve in presence of water. Therefore, keeping the produced water with high TSS during the reinjection in wells, these solids would create emulsion and it might clog in the pipeline and reservoir, blocking it and creating corrosion and create problems of obstruction of the reservoir pores. Then, to avoid future contamination of water and corrosion of PW, is required a treatment for the removal of these suspended solids.

4.2.1.2. Conductivity (TDS) and Total Dissolved Solids

Conductivity is mostly related to dissolved solids content of the water. In comparison to MICOA regulation and IFC standard, the samples high conductivity ranging from 10,000 to 16,600 µS/cm, compared to 1,000 to 2,500 µS/cm established by the standard. From the ***Graphic 2*** the injection of corrosion inhibitor in PW, it did not make changes in positive way and the conductivity sill high. The no change/reduction of conductivity might be due high presence of dissolved salts and other inorganic materials related to presence of residual hydrocarbon which is directly related to the concentration of ions in the water.

Graphic 2 - Conductivity results vs the regulation limits

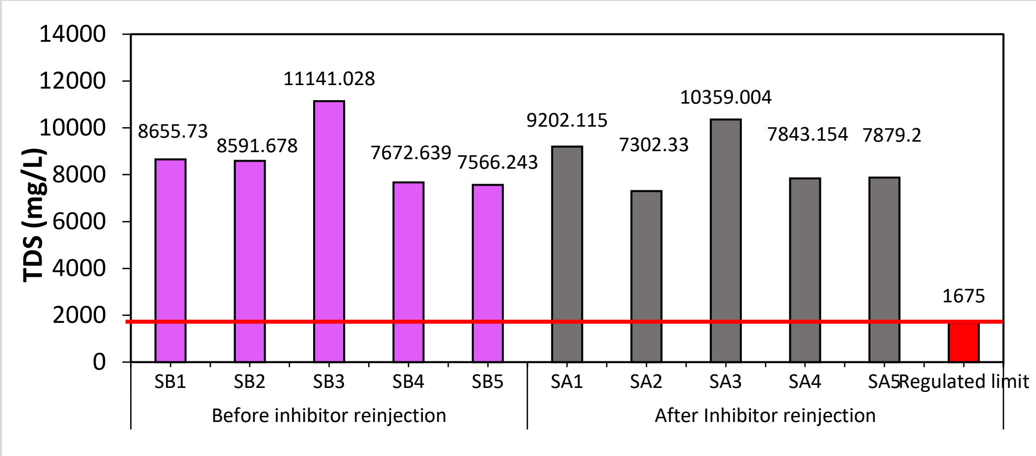


Conductivity and salinity have a strong correlation. As conductivity is easier to measure, it is used in algorithms estimating salinity and TDS, both of which affect water quality and aquatic life. According to (EPA, 2001), besides the conductivity being related to Total Dissolved Solids, itself, it is a property of little interest to a water analyst but it is an invaluable indicator of the range into which hardness and alkalinity values are likely to fall. So, most of the water with high conductivity, shows high quantity of TDS elements and salt content presence.

As conductivity parameters is easier to measure, it is used in algorithms estimating salinity and TDS, both of which affect water quality and aquatic life. So, in order to determine the Total Dissolved Solids (TDS), there were used the following formula, ***Total Dissolved Solids (mg/l) = Conductivity (µS/cm) x 2/3***. This formula is mostly used to convert de conductivity to TDS for many surface waters, whether there is no TDS available.

Therefore, referring to Total Dissolved Solids (TDS), it can be visualized that even before or after the reinjection of corrosion inhibitor in PW, very high values are presented, ranging from around 73000 to 110000 mg/L, more than the expected and established by standards (650 – 1675 mg/L), as presented in above ***Table 11*** and ***Graphic 3***, below.

Graphic 3 - TDS results vs the regulation limits

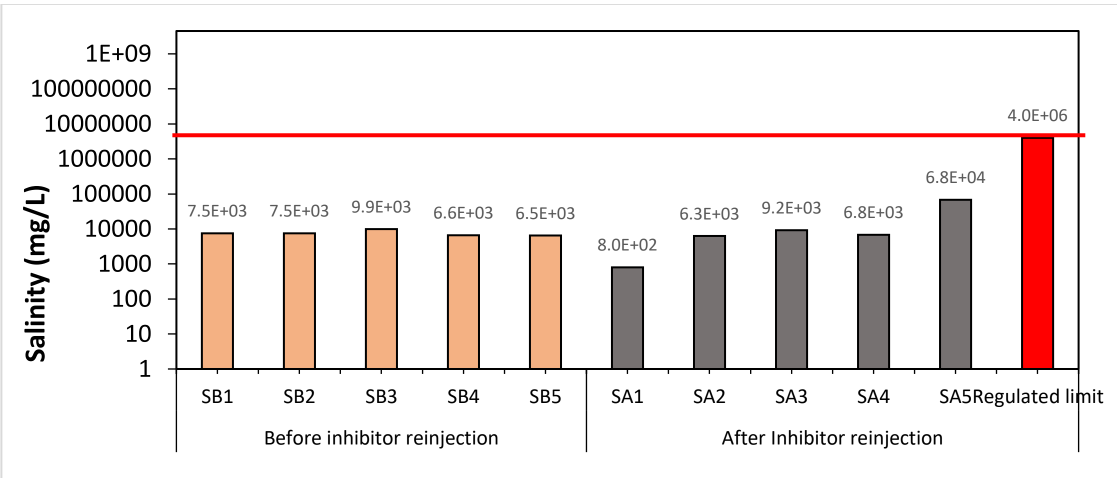


It is very possible to find this PW water has high value of conductivity. Based on (Veil, 2007), This PW might be commonly identified by organic and inorganic elements, such as insoluble carbon, some amount of H2S, the major components that result in salt water. If these two elements are available in produced water, they can result in sweet corrosion for CO2 and sour Corrosion for H2S in presence of water. The corrosion could damage the equipment and pipeline affecting the production process and increasing the cost of maintenance. To avoid future problems to the factory and future environmental contamination, is requiring a treatment for the removal of these dissolved solids.

4.2.1.3. Salinity and Density

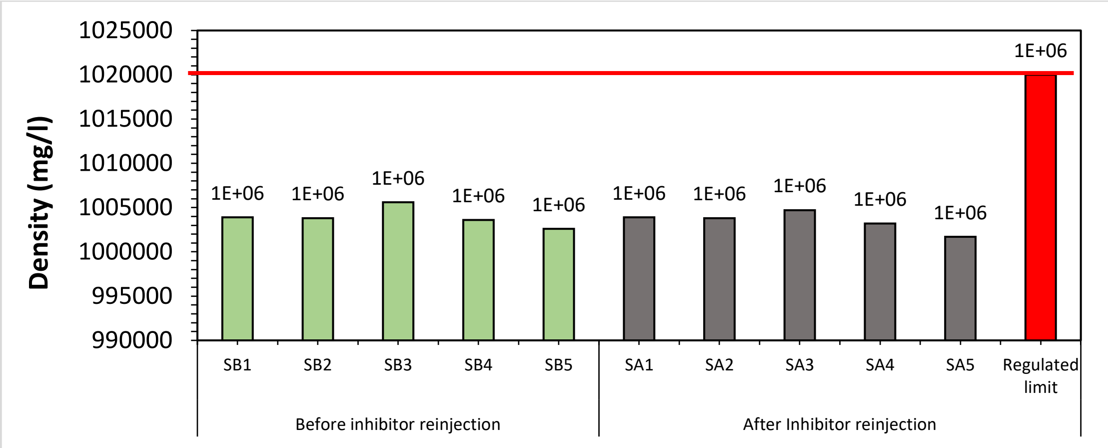
For salinity, it can be observed in ***Table 11*** that samples before and after injection of corrosion inhibitor reinjection, present lower value around 800mg/L to 6.8×10^4mg/L, in comparison to what is expected and established by standards (~ 4×10^6 mg/L) as represented in below ***Graphic 4***.

Graphic 4 - Salinity results Vs the regulation limits



The density of the water plays the same roll with results with the salinity, presenting lower value around 1.00 $x10^6$ mg/L, in comparison of the expected ($1.02x10^6$ mg/L) as represented, above and Graphic 5, below.

Graphic 5 - Density results vs the regulation limits

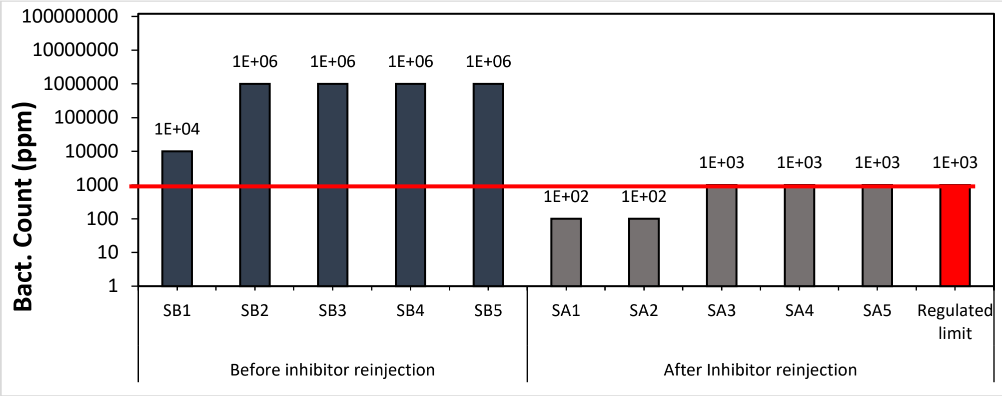


For both, salinity and density of the produced water are slight lower than the expected or regulated ones. It important to keep and reduce as lower as possible the amount of the salinity because, if it is high quantity, it could result to aquatic destruction in water (as body receptor, sea, underground and superficial water).

4.2.1.4. Bacteria count

Referring to Bacteria count, it can be observed before inhibitor injection in PW, the samples are showing higher parameter values between of 1x104 mg/L to 1.0x106 mg/L, three (3x) times higher than the regulated amount (< 1.0x103 mg/L), as show in **Error! Reference source not found.** below. The total opposite happen after injection of the corrosion inhibitor, the biocide and XLAmine, the bacteria count in PW, reduced three (3x) to four (4x) in comparison to the previous values, around 1.0x103 mg/L, as represented in ***Table 11***, above and ***Graphic 1***, below.

Graphic 6 - Bacteria count results vs the regulation limits



Based on (Larsen, 2020) and (Eckert & Skovhus, 2011), the corrosion of a material when the presence of microorganisms plays a role known as microbiologically influenced corrosion (MIC), where activities of bacteria in colony creates biofilms on surfaces of materials or in environments that is directly in contact with the materials. Most metals, as well as some nonmetals, can be affected by this type of corrosion.

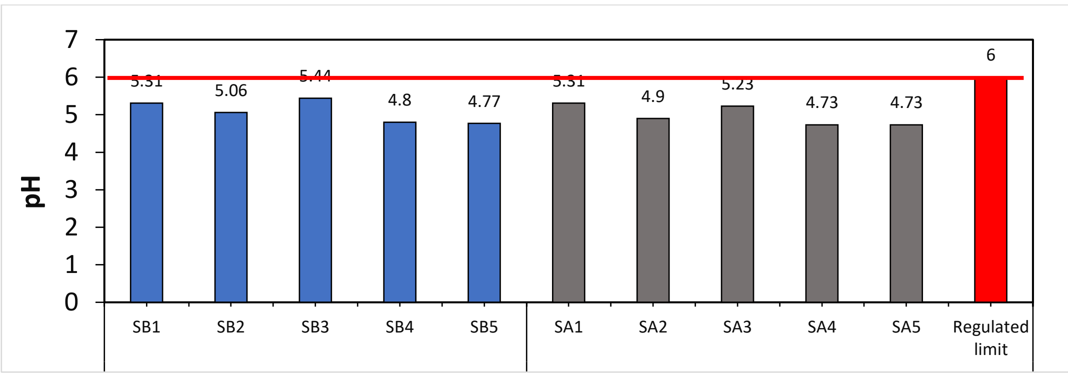
So, if the amounts of bacteria are high, more biofilms will be formed and can easily clog equipment and pipelines. They can also form difficult-to-break emulsions and hydrogen sulfide, which can be corrosive. It's important for the company continuously keep working on controlling the bacteria count in the water, in order to reduce or avoid clay swelling around the well bore and cause the corrosion to the pipeline and other part of the equipment in the CPF.

4.2.1.5. pH and Temperature

Referring to the pH in PW before and after the injection of the Biocide and XLAmine all the PW samples show high levels of acidity, with pH ranging from 4.73 – 5.31, below the specified range (6 – 9) as represented in ***Table 11***, above and

Graphic 7 below.

Graphic 7 - pH results vs the regulation limits

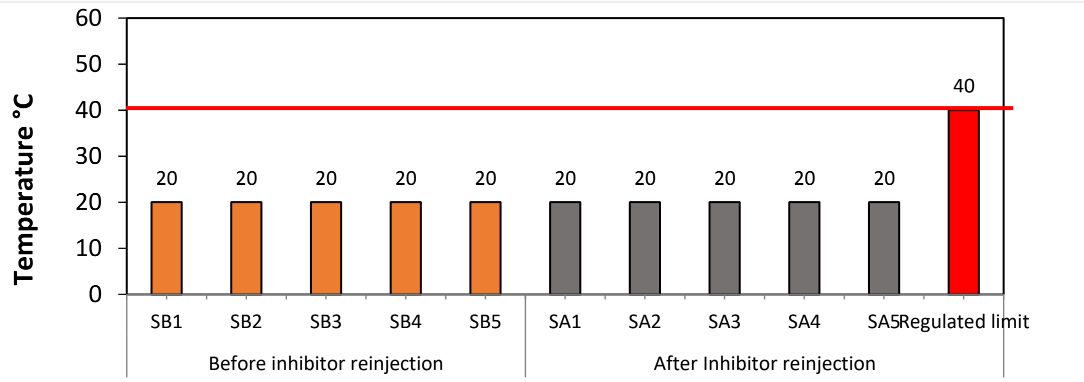


For launching the produced water to the environment or reinject into the well (AER, 1994), the pH of water must always be around 6.0 and 9.0 (based on standard (IFC, 2007)), and all the pH below or over this interval must be treated first.

According to Prawoto, Ibrahim & Wan Nik, (2009), a decreasing of pH (acidity increase), affect significantly the corrosion rate, by increasing it. This happen because low pH solutions accelerate corrosion by providing hydrogen ions, where hydrogen attacks and damages the surface of steel and increases the weight loss. For EPA (2001), water with a pH value under 7 may dissolve metals to an extent which, if not causing deterioration of storage tanks or distribution mains, may nonetheless give rise to undesirable metal concentrations. Such waters are also unlikely to deposit calcium carbonate as a protective scale in pipes.

Referring to the temperature of the PW, the data show that all the samples, before and after the injection of corrosion inhibitor, the temperature were static, 20°C (see ***Graphic 8***), with no changes in comparison to the specified range (40 °C) as represented in ***Table 11***, above.

Graphic 8 - Temperature results vs the regulation limits



According to Prawoto, Ibrahim, & Wan Nik (2009), The temperature plays an important role in accelerating the corrosion rate of metals. The higher the temperature is, the higher the corrosion rate is. The chloride concentration also increases the corrosion rate. As Lower pH will significantly increase the corrosion rate of the steal, pipeline on any machinery covered by metal, the reverse happens with the temperature, by increasing temperature, the corrosion rate will increase.

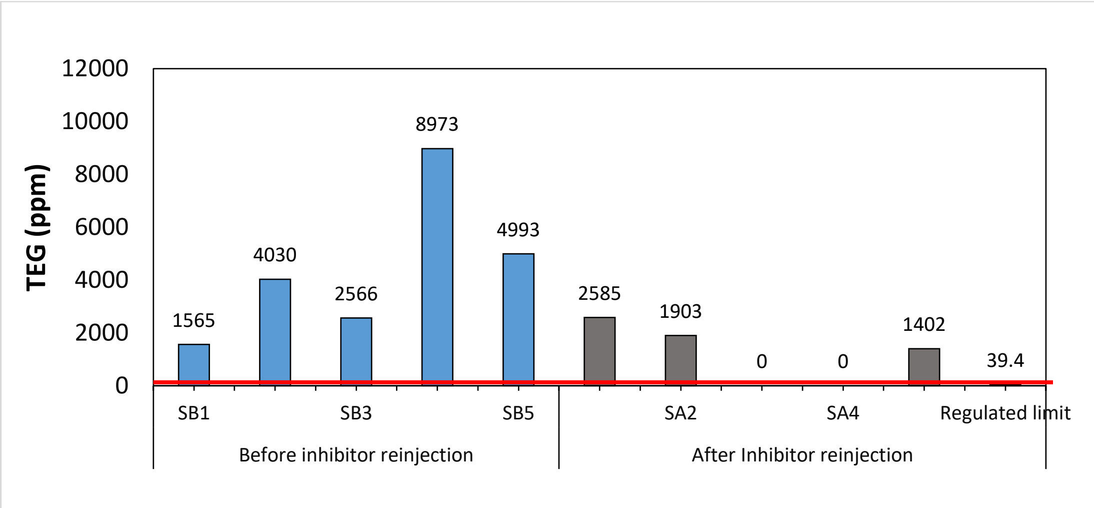
But, according to the results, the temperature, salinity and density of the water are in good range, in comparison to standard. the bacteria count, first show a high value, but, during the time, with injection of biocide, the bacteria count reduced considerably. These parameters might not be the unique factor of corrosion, various parameters together and its combinations might influence and increase the reaction process.

4.2.1.6. TEG

For TEG (triethylene glycol) all the PW samples, before and after the injection of the Biocide and Xlamina, show high value of TEG ranging from ~ 200 – 9000 ppm, more than ten time (10x) to the specified range (20-39.4 ppm) as represented in ***Table 11***, and

Graphic 9.

Graphic 9 - TEG produced water results vs the regulation limits



At high concentration, if TEG is released in indoor or outdoor environment as a liquid spray (aerosol), vapor, or mist, it can contaminate the environment. If it gets in contact with water, it might also poison the water. Is likely that the TEG can contaminate also food and agriculture product if they are released in form of Spray, aerosol and its unlikely to poison the environment when it is in spread as water vapor.

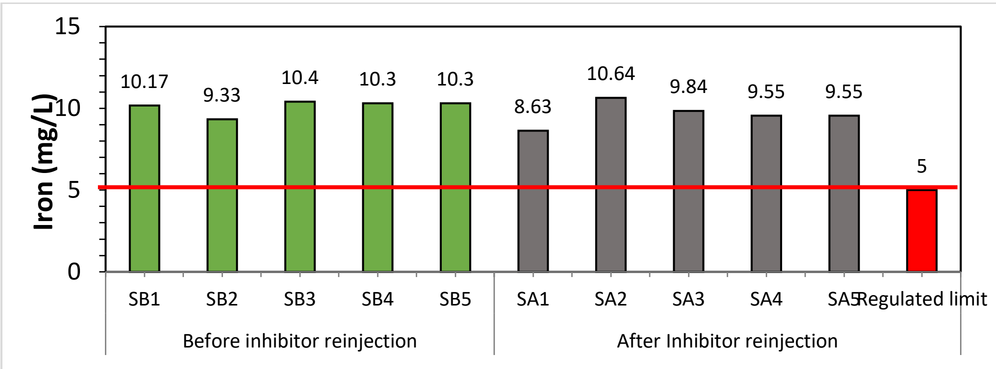
4.2.2. Organic and Inorganic

4.2.2.1. Iron

Referring to iron (Fe), all the PW samples, before and after the injection of the corrosion inhibitor, show high values ranging from 6.33 mg/L to approx. to 11 mg/L over the regulation specified range (<5) as represented in ***Table 11***, above and

Graphic *10* below.

Graphic 10 - Iron produced water results vs the regulation limits

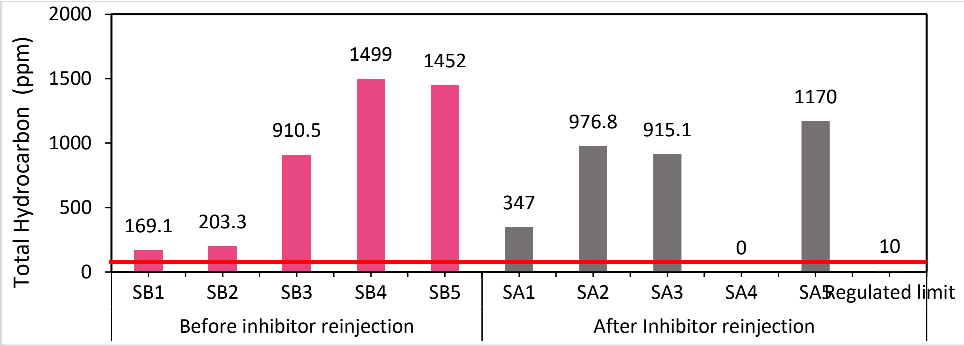


Iron is a typically metals found in produced waters, including zinc, lead, manganese and barium. Metals concentrations in produced water are often higher than those in seawater. According to Veil et al (2007), Iron can cause production problems, because when it is part produced water content, it can react with oxygen in the air to produce solids, which can interfere with processing equipment, such as hydrocyclones, and can plug formations during injection or cause staining or deposits at onshore discharge sites.

4.2.2.2. Total Hydrocarbon

For Total Hydrocarbon, all the PW samples, before and after the injection of the corrosion inhibitor, show high amount of low hydrocarbon available, ranging from 100 ppm to approx. to 1100 ppm, ten times (10x) higher than the specified by the regulation, less than 10 (<10) ppm, as represented in, above ***Table 11*** and ***Graphic 11*** below.

Graphic 12 - Total Hydrocarbon results vs the regulation limits



Studies indicate that the produced water discharge from gas/condensate platform, with BTEX, benzene, toluene, ethylbenzene and xylenes, are about 10 times more toxic than produced water discharged from oil platform. Some residual hydrocarbon components can be present as suspended solids (TSS) and when they are in contact with water might create difficult-to-break emulsion, which normally clog it in the pipeline and reservoir, blocking it and creating corrosion.

4.3. Environmental Impact of the Produced Water to Environment and Equipment

Produced water can mostly be reused for several purpose, such us irrigation, cleaning, launch to the body receptor for aquaculture or another purpose, unless it is or can treated to remove all the impurities present in the water, otherwise, the produced water can contaminate the reception body and harm the entire environment and increase the climate change.

In this section will be described the main impact that the physicochemical, organic and inorganic parameter found in the water such as TSS, TDS, Conductivity, TEG, Salinity, Bacteria count, Density, pH, Temperature, Total hydrocarbon, Metal iron can affect the environment, including, the pipeline, equipment, the underground water and soil when it is launched in high quantity before any treatment.

The impact of physicochemical, organic and inorganic element i will be analyzed based on different standards such (EPA, 2001), (EPA, 1980), IFC (2014), and other related studies such as (Hedar & Budiyono, 2018), Neff, Lee, & DeBlois, (2002), (Ahmaduna, et al., 2009) and other studies according the possibilities of these elements affect the environment and significance of each element to the environment.

The table 18 below represents a resume of significant impact of physicochemical, organic and inorganic element in water and the environment. Each parameter can affect a certain area of contact such as living body, soil and water, equipment and how they interfere in flora and fauna, affect the equipment surface, cause corrosion and damage and finally how they affect the livestock by poisoning the water, the soil and plant present in affected area.

Comparing all the parameter and it is impact to the environment, as shown in details on the ***Table 12*** below, the physicochemical parameter represents high risk of corrosion and damage of the pipeline and other metal surface equipment's.

Table 12 - Significant Impact of physicochemical, organic and inorganic element in produced water

<table>
<tr><th rowspan="2">Impacting Element</th><th rowspan="2">Significance</th><th colspan="3">Affected area</th><th rowspan="2">Significant environmental Impact Physicochemical element in water</th></tr>
<tr><th>Living body</th><th>Soil & water</th><th>Equipment</th></tr>
<tr><td>Conductivity & Total Dissolved Solids (TDS)</td><td>High</td><td>X</td><td>X</td><td>X</td><td>Conductivity and total dissolved solids (TSD) are related and determine the overall ionic effect in a water source. High conductivity represents high quantity of dissolved solid and following environmental impact that can be generated:
Interference in flora and fauna
– The conductivity and TDS value is a measure of inorganic and organic materials present in water. Waters with high TDS cause cells to shrink, disrupt organisms, movement, and make them afloat or sink beyond their normal range;
– The hardness of water can cause impact on fish and other aquatic life when appears same metal to be the affect the presence of these ions has on the other more toxic metals such as lead, cadmium, chromium and zinc;
Corrosion and equipment damage:
• Total Dissolved Solid can also be represented by elements such as CO2 and H2S present in small quantity, the major components that forms salt water. If these two elements are available in water, they can generate the sweet corrosion for CO2 and sour Corrosion for H2S in presence of water.
• High TDS value indicates high salt content, alkalinity or hardness and can consequently affect taste of the water column and main factor of encrustation and corrosion of metallic surfaces by waters in dissolved solids causes problems with industrial equipment and boilers.
• For domestic case, it can affect as well: as domestic plumbing, hot water heaters, toilet flushing mechanisms, faucets, and washing machines and dishwashers. Elevated dissolved solids can cause "mineral tastes" in drinking water.</td></tr>
</table>

Total Suspended Solids (TSS)	High	X	X	X	**Interference in flora and fauna** • Indirect effects of excess TSS are primarily the elimination of desirable food plants and habitat-forming plant species. • For plant and animals, TSS can clog fish gills, either killing them or reducing their growth rate. They also reduce light penetration. This reduces the ability of algae to produce food and oxygen. When the water slows down, as when it enters a reservoir, the suspended sediment settles out and drops to the bottom, a process called siltation. This causes the water to clear, but as the silt or sediment settles it may change the bottom. The silt may smother bottom-dwelling organisms, cover breeding areas, and smother eggs. **Corrosion and equipment damage:** • Using water with high amount of TSS for reinjection, would create problems obstruction of the reservoir pores. TSS might contain small residual hydrocarbon components and when they are in contact with water might create emulsion which normally clog it in the pipeline and reservoir, blocking it and creating corrosion. **Livestock** • Agricultural uses of water for livestock watering are limited by excessive dissolved solids and high dissolved solids can be a problem in water used for irrigation.
Salinity	High	X	X	X	**Corrosion and equipment damage:** • High Salt content might be a main factor of increasing of TDS values, it might increase hardness of water can consequently affect taste of the water column and become main factor of encrustation and corrosion of metallic surfaces causing problems with industrial pipeline and other equipment. **Interference in flora and fauna** • High amount of salinity could result to aquatic destruction, if launched in reception body in water (as body receptor, sea, underground and superficial water).

Bacteria count	High	–	–	X	**Corrosion and equipment damage:** • According to (Larsen, 2020) and (Eckert & Skovhus, 2011) Activities of bacteria can create biofilms on surfaces of materials, or in local environments that directly contact materials, can result in microbiologically influenced corrosion; and most metals, as well as some nonmetals, can be affected by this type of corrosion. This process of corrosion might affect the company in term of cost of maintenance. • Bacteria can clog equipment and pipelines. They can also form difficult-to-break emulsions and hydrogen sulfide, which can be corrosive.
pH	High	X	X	X	**Corrosion and equipment damage:** • If the pH decreases, the acidity increase. If the acidity of the water increases more significantly and easy will affect the corrosion rate in the equipment because low pH solutions accelerate corrosion by providing hydrogen ions, where hydrogen attacks and damages the surface of steel and increases the weight loss. • Water with a pH value under 7 may dissolve metals to an extent which, if not causing deterioration of storage tanks or distribution mains, may nonetheless give rise to undesirable metal concentrations. Such waters are also unlikely to deposit calcium carbonate as a protective scale in pipes and it will be costly for the companies to maintain the equipment.
Temperature	Low	–	–	X	According to the parameter values, the water is good quality condition and may not affect significantly the quality of water. In case of increasing the temperature, according to (Popoola et al, 2013), Internal corrosion and damage in wells and pipelines would happen, and would be influenced also with presence of CO2 and H2S content, and surface condition of the steel. **Corrosion and equipment damage:** • The temperature might influence the pH and significantly raise the corrosion rate. As Lower pH will significantly increase the corrosion rate of the steal, pipeline on any machinery covered by metal, the reverse happens with the temperature, by increasing temperature, the corrosion rate will increase.
TEG (triethylene glycol)	Low	X	X	–	Based on (Agency for Toxic Substances and Disease Registry (ATSDR), 1997), the TEG (Triethylene glycol) at high concentration, if it's released in indoor or outdoor environment as a liquid spray (aerosol), vapor, or mist, it can contaminate the environment. If it gets in contact with water, it might also poison the water. Is likely that the TEG can contaminate also food and agriculture product if they are released in form of Spray, aerosol and its unlikely to poison the environment when it is in spread as water vapor.

Heavy metal Iron (Fe)	High	X	X	X	**Corrosion and equipment damage:** • Iron, severe case, can cause production problems in factory, because in produced water, it can react with oxygen to produce solids, which can interfere with processing equipment, such as hydrocyclones, and can plug formations during injection or cause staining or deposits at onshore discharge sites. • The iron precipitate will cause considerable damage by means of clogging action and hinder the respiration of fishes (EPA, 1993). Elevated iron levels in water can cause stains in plumbing, laundry, and cooking utensils, and can impart objectionable tastes and colors to foods. (Rice, Baird, & Eaton, 1999) According to (EPA, 2001), The metal is quite harmful to aquatic life, as evidenced by laboratory studies, but in nature the degree of toxicity may be lessened by the interaction of the iron with other constituents of a water. Should the metal be converted to an insoluble form then the iron deposits will interfere with fish food and with spawning.
Total hydrocarbon content	High	X	X	X	• According to (Hedar & Budiyono, 2018), The produced water discharge from gas/condensate platform, with BTEX, benzene, toluene, ethylbenzene and xylenes, are about 10 times more toxic than produced water discharged from oil platform. If hydrocarbon content goes directly to the soil and water, it might: • Might affect at short-term and long term the quality of soil, water as well as human health. Petroleum hydrocarbon contaminated soil affect plant growth, and reduce yield of crop from an agricultural region. Petroleum hydrocarbon contaminated water affect flora and fauna of aquatic ecosystems. Petroleum hydrocarbon contamination is highly hazardous to the environment. It has severe impacts on the plants as well as animal ecosystem including human health.

Source: Autor (2020)

The pH of pw is much lower compared to the standard, representing more acidity. As more acidity is the water becomes high, the greater the chances of corrosion process occurring in all equipment made of metal (pipeline and other equipment). associated with temperature, the higher the temperature of the water or the environment, would considerably increase the likelihood of process corrosion. therefore, it is possible to notice that there is a strong relationship between the pH and the temperature of the environment and water.

The conductivity and total dissolved solids (TSD) present are very high. Conductivity represents the amount of total dissolved solids (TSD) and the possibility of conduction of electric current in water. High conductivity can be represented by a high number of dissolved substances, chemicals and minerals, such as salts. Therefore, it is possible to note that these high conductivity values increase as salinity increases, the presence of elements such as magnesium and calcio, and significantly affects the chances of corrosion of the equipment. Therefore, it is possible to conclude that the high level of conductivity is due to the high number of minerals such as Calcium, salt, magnesium and other minerals.

The bacteria count also affect considerably corrosion process. The bacteria when present in high quantity they tend to biofilms on surfaces of materials, or in local environments that directly contact materials, can result in can result in microbiologically and difficult-to-break emulsion that easily clogs the equipment and corroding the pipelines. If the iron (Fe) is present in high levels in water can cause stains in plumbing, laundry, and cooking utensils, and can impart objectionable tastes and colors to foods e also can contaminate the water. The process of corrosion that result from action phytochemical element might affect significantly the cost to maintain pipeline and the damaged part of the factory.

The hydrocarbon content less affects the process of corrosion but affect at short-term and long term the quality of soil, water as well as human health. Petroleum hydrocarbon contaminated soil affect plant growth, and reduce yield of crop from an agricultural region. Petroleum hydrocarbon contaminated water affect flora and fauna of aquatic ecosystems.

Comparing all the elements, the ones that needs to be highly considered as a treat for factory, human life and quality of soil, water, and plant are Conductivity & Total Dissolved Solids (TDS), Total Suspended Solids (TSS), pH, Heavy Metal, Total Hydrocarbon Content and battery count because these elements are in high quantity, they might be reduce to meet the standard in order to avoid future problems such corrosion, equipment damage, contamination of soil, water, plant and livestock.

4.4. Evaluation of Efficiency of Corrosion Inhibitor Agents

The produced water resulting from SPT facility contain some Total Solid, Conductivity, Dissolved Oxygen, metals, Bacteria Count, Total Hydrocarbon, salinity and other elements in high quantity, which can react with the metal surface of the pipeline and equipment causing corrosion and damage the pipeline and equipment, consequently cause spillage of PW that can contaminate the environment. In order to control and reduce the chances corrosion one pipeline and equipment, the SPT added XLAmine and Biocide, chemical compounds that act as corrosion inhibitors in PW, which decreases the corrosion rate of a metal and several non-metal surface of the pipeline and equipment.

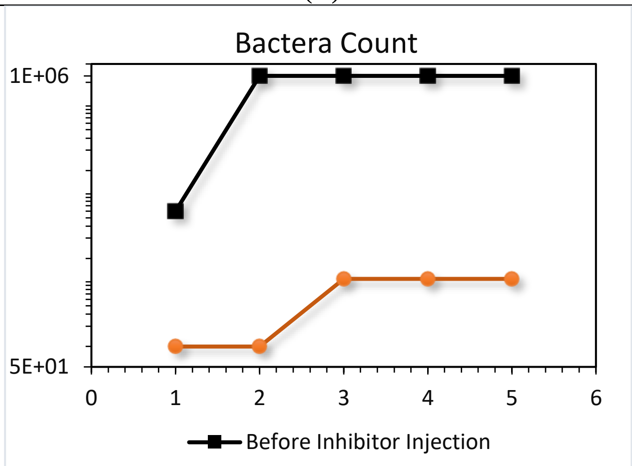
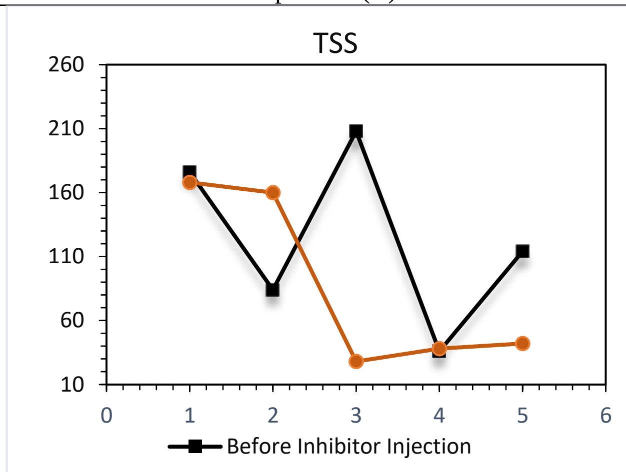
The XLAmine is used as clay swelling inhibitor to reduce clay swelling around the well bore and, it is normally pumped into the PW stream at PW injection pump suction in dosage between 50-3000ppm. While the biocide is injected along the flowline and at the wellhead itself (around 200ppm injection rate in each case), in order to avoid multiplication of bacteria that when are in contact with other elements can form biofilms on surfaces of materials, or in local environments that directly contact materials, can result in can result in microbiologically influenced corrosion in most metals, as well as some nonmetals. So, if the amounts of bacteria are high, more biofilms will be formed and can easily clog equipment and pipelines. The bacteria in contact with some suspended solid and hydrocarbon particle can also form difficult-to-break emulsions and hydrogen sulfide, which can be corrosive

Therefore, at this chapter, we want to understand, by PW trend data illustration, how the corrosion inhibitors, Biocide and XLAmine, influenced on reduction of corrosion process and reduction of level of contaminants or level of physicochemical, organic and inorganic parameters in the water, such as Bacteria counts, TDS, conductivity, TSS, pH, total hydrocarbon, salinity, density, Heavy metal (Iron), TEG and Temperature.

4.4.1. Efficiency evaluation of corrosion inhibitor agents and their effect on other water parameters

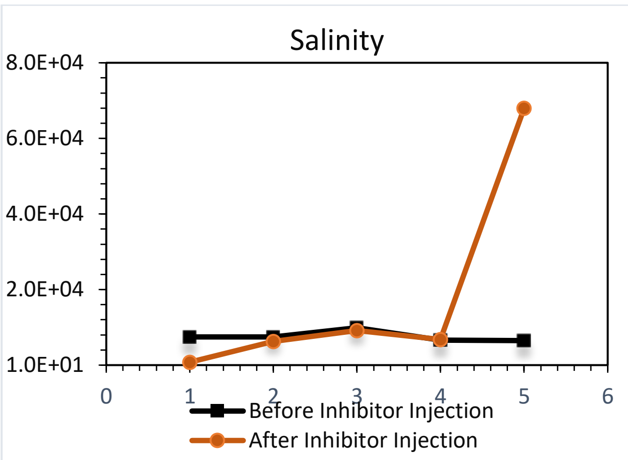
Starting with Bacteria count, based on results available on ***Table 11*** it can be observed that all the samples before injection of corrosion inhibitor, show higher values between of $1x10^4$ mg/L to $1.0x10^6$ mg/L, three (3x) times higher than the regulated amount (< $1.0x10^3$ mg/L). But, from the below figure (***Graphic 13 A***, left) is possible to see that after injection of biocide and XLAmine, the amount of bacteria count dropped drastically to $1.0x10^3$ mg/L, three (3x) to four times (4x) in comparison to the initial value. The similar happened with TSS amount, after the injection of corrosion inhibitor in PW, the figure (***Graphic 13 B***, Right) shows a considerable drop of TSS amount dropped until to 30 mg/L in 3 last samples, decreasing more than three times (3x) the initial value (around 80 to 210 mg/L).

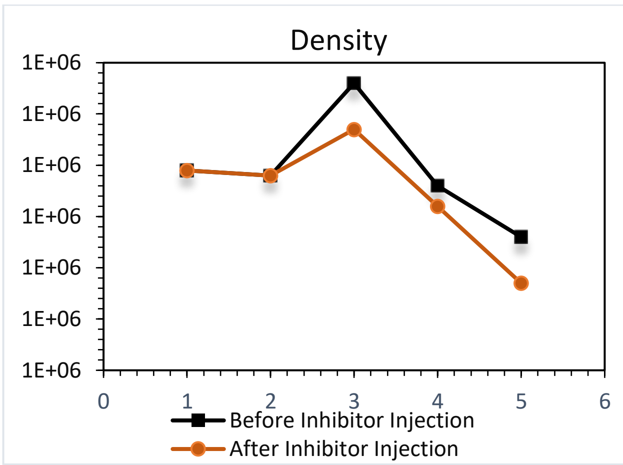
Graphic 13 - Effect of Biocide and Xlamina on Bacteria Count (A) and TSS (B) Reduction

(A)	Graphic 18 (B)
	

For the salinity, as is shown in table 17, after de injection of corrosion inhibitor the value of the salinity in PW did not change considerably at the beginning, presenting the same trend behavior as before the inhibitor injection, although the salinity of last PW sample had raised (***Graphic 14A***, Left). While the salinity become almost static, the density of PW after dropped slightly with effect of corrosion inhibitor, (***Graphic 14B***, Right).

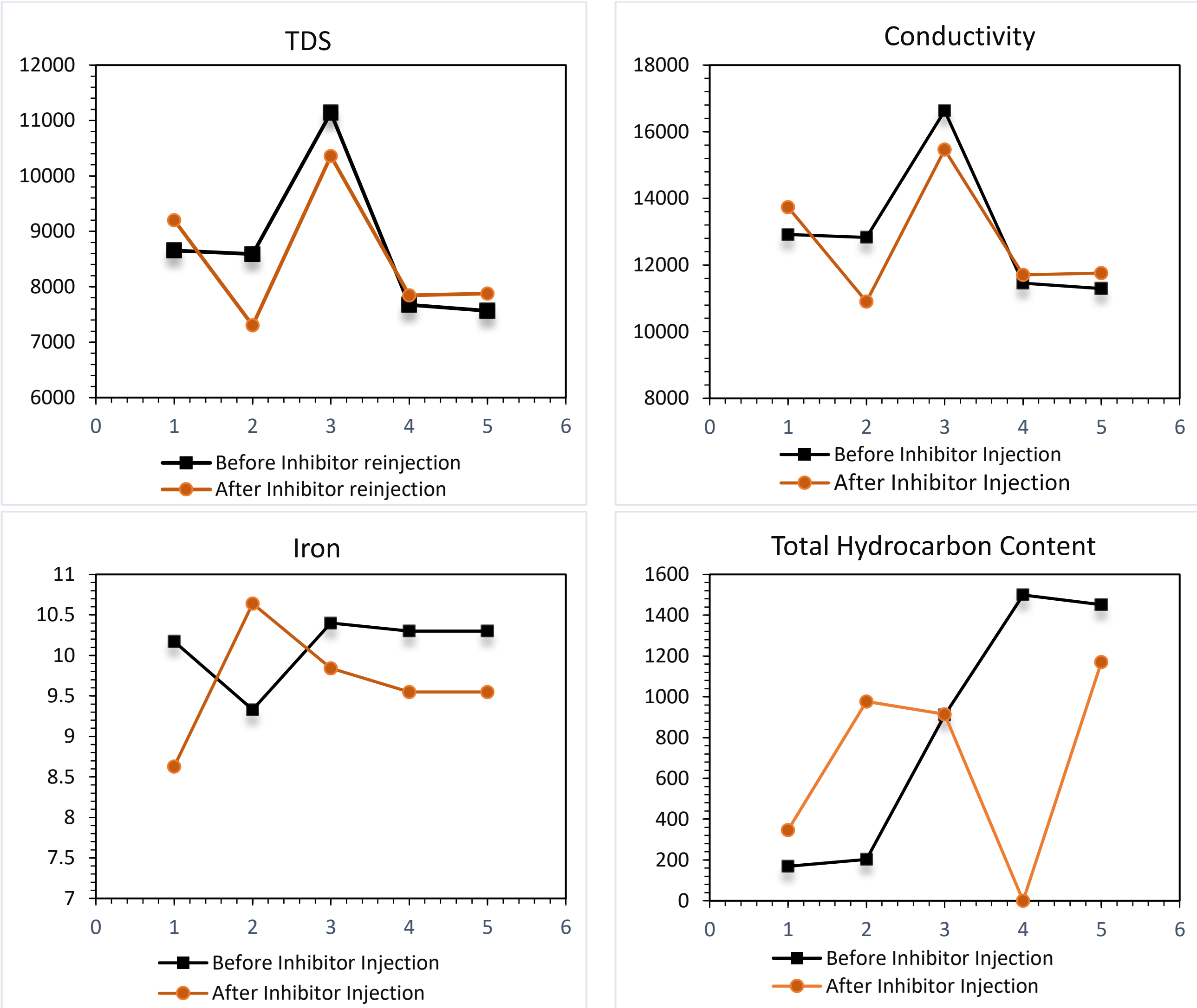
Graphic 14 - Effect of Biocide and Xlamina on Salinity (left) and Density (rigth) Reduction





The parameters conductivity, TDS and Iron and total hydrocarbon, had slight parameter changes, after injection of corrosion inhibitor, although there is some oscillation in value (raising and decreasing). It can be noted that the values of theses parameters did not decrease or increased so much in comparison with same parameters of PW before corrosion inhibitor injection, even though all of them do not meet the PW standard requirement for discharging into the environment (***Graphic 15***)

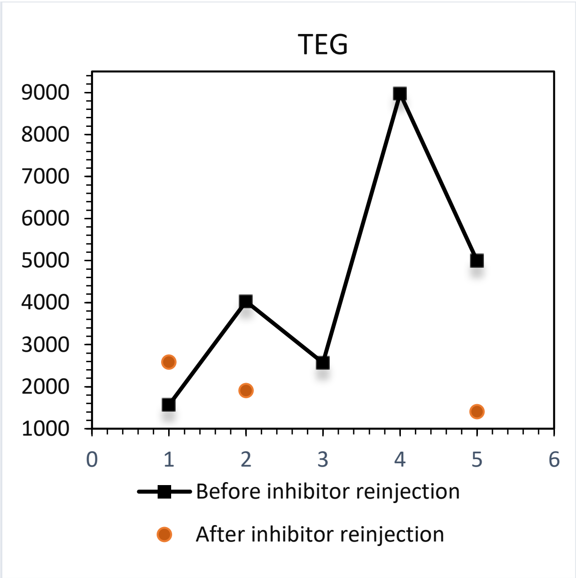
Graphic 15 - Effect of Biocide and Xlamina on TDS & Conductivity (above) , Iron (Fe) & Total Hydrocarbon (down)



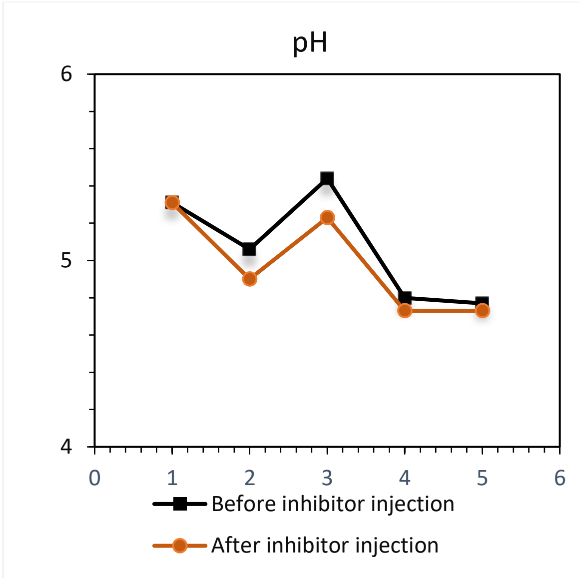
Referring to pH, all PW samples, before biocide and XLAmine injection, presented lower PW values, ranging from 5.4 to 4.8, represented higher acidity. After the injection of the corrosion inhibitor the values became still low ranging from 5.3 to 4.7 (see below ***Graphic 16B***), more acid than is established in the water quality standards (standard pH of 6 to 9). But for the TEG, beside the value are not all available is possible to find that there is considerable dropping of the TEG value after corrosion inhibitor injection. According Agency for Toxic Substances and Disease Registry (1997), the TEG (triethylene glycol), most time are in form of vapor or spray (aerosol), and they can disappear during the time due to its properties, so it possible that the reduction of TEG after Inhibitor injection might be influenced by due it's properties, by releasing it in form of vapor.

Graphic 16 - Effect of Biocide and XLAmine on pH (A-left) and TEG (B-right)

(A)



(B)



The trends reveled that the presence of biocide and XLAmine, the corrosion inhibitor, contributed considerably on reduction of the bacteria count in produced water more than 4x time, and slightly reduce the amount of TSS and density in produced water, although these two parameters did not meet standard requirement. Probably, the reduction of the level of this parameters, bacteria count, TSS and may have great influenced on reduction of corrosion process one the pipeline, equipment and metal superficies.

The salinity and density parameter did not change enough, and the corrosion inhibitor did not affect them considerably. But it is possible to note that the values of these two parameters are within the parameters established and do not necessarily need to be treated. Comparing the values of conductivity, TDS and iron and total parameters of hydrocarbons, it is possible to note that the corrosion inhibitor did not significantly affect both the above parameters enough to meet the preselected standard requirements.

For the pH, the corrosion inhibitor affected it greatly, contributing to the reduction of the pH value of PW to the most acidic possible, with a pH of 4.7. According to Prawoto, Ibrahim & Wan Nik, (2009), a decreasing of pH, influence on acidity increment and significantly the increase corrosion rate of any material. This happen because low pH solutions accelerate corrosion by providing hydrogen ions, where hydrogen attacks and damages the surface of steel and increases the weight loss**.**

Thus, in terms of efficiency, the injection of corrosion inhibitor in PW, was more efficient on was more efficient in significant reducing in four (4x) times more the number of bacteria count and TSS in the production water. The corrosion inhibitor was not efficient and did not considerably and positively affect other parameters, such as temperature, conductivity, TDS and iron and total hydrocarbons. But, for the pH parameter, the corrosion inhibitor negatively affected it and reduced reducing the pH value up to 4.7, increasing their acidity level, one of the major causes of corrosion. Therefore, different from Bacteria count, the parameter such as conductivity, TDS, TSS, pH, iron and total hydrocarbons needs a treatment method urgently to reduce the chances of increasing the corrosion process to factory equipment during the time and avoid damage and contamination of the environment. The salinity, density and bacteria count must be controlled continuously in order to avoid corrosion effect.

4.5. Evaluation of Suitable Technology of Produced Water Treatment

This subchapter presents a proposal of method or technology of treatment of PW, suitable for the reduction of pollutants such as conductivity, TDS, TSS, pH, iron and total hydrocarbons and salinity present in the water produced. The method to be proposed will be selected from several existing technologies or methods applicable for the parameters mentioned above and obeying the following technology criteria: estimating the costs to run the technology, efficiency and efficacy, number of steps necessary to treat water among others. The technology to be chosen was also analyzed based on the current and future production perspective produced water at Sasol Petroleum Temane. It is hope that the chosen technology does not limit the company to the possibility to study other alternatives management and treatment technology based on the economic condition, efficiency, and specialist availability.

4.5.1. Selection and Characterization of produced water applicable management and treatment technologies

The general objectives of selecting a proper technology for treating the gas produced water and contaminant found in Sasol Central Processing Facility is to remove hydrocarbon particle, total suspended particles (TSS), soluble organics, total dissolved particles (TDS), reduce the water conductivity, remove excess water hardness in the water, correct the pH, remove heavy metal in order to avoid damage to factory equipment, contaminate the environment and harm public health. According (Arthur, Langhus, & Patel, 2005) and (Igunnu & Chen, 2014), there are several types of technologies that can used for, such as, the membrane filtration, thermal treatment and biological, physical & chemical technologies (media flotation, gas flotation, evaporation pond, MPPE technology, Adsorption, hydrocyclone, trickling filter).

According to Igunnu & Chen (2014), The membranes are microporous films with specific pore ratings, which selectively separate a fluid from its components. It is used separates suspended particles, can be used as a standalone technology for treating industrial wastewater, but most of membrane technologies are usually employed in water desalination. The thermal treatment technologies of water are employed in regions where the cost of energy is relatively cheap and have been used to achieve higher efficiency, but the thermal separation process is also the technology of choice for water desalination and they are more attractive and competitive in treating highly contaminated water Different from other technologies such as Multieffect distillation, chemical oxidation, adsorption, macro-porous polymer extraction technology, evaporation pond, gas flotation, hydrocyclone and trickling Filter that are mostly used for all type of produced water, mainly from gas production process. They are suitable to treat most particles such as hydrocarbon particle, total suspended particles (TSS), soluble organics, total dissolved particles (TDS), remove excess water hardness and heavy metal.

Based on the above statement, can be applied a one or a combination of following standalone, physical, biological and chemical produced water management and treatment technologies. Therefore, to treat produced water from Sasol CPF, were selected the following technologies and management techniques:

I. (1) Multieffect distillation (MED)
II. (2) Chemical Oxidation
III. (3) Adsorption
IV. (4) Macro-porous polymer extraction technology
V. (5) Evaporation pond
VI. (6) Gas flotation
VII. (7) Hydrocyclone
VIII. (8) Trickling Filter,

The selected technologies, due to its characteristics and ability, they are able treat PW with characteristics similar to PW from Sasol and remove hydrocarbon particle, total suspended particles (TSS), soluble organics, total dissolved particles (TDS), remove excess water hardness and heavy metal. For that, these technologies will be first characterized and then ranked in order find the better or the several best that would be used and combined with others and applied in Sasol Central Processing Facility.

4.5.2. Characterization and comparison of selected produced water technologies

The eight selected technologies for PW are characterized and compared each other in below tables (***Table 13*** & ***Table* 14**), based on cost, the ability to treat the PW, consumption of supplement, chemical and energy, the life time, the backward and advantages according (Arthur, Langhus, & Patel, 2005). After the characterization, the PW will be ranked to find the best ones or the better one, based on (ALL Consulting, 2003) and (Arthur, Langhus, & Patel, 2005) ranking methodology.

Table 13 - Characterization and comparison of produced water management and treatment technologies applicable for oil and gas PW I.

Technology	Adsorption	Hydrocyclone	Chemical Oxidation	Gas Flotation
Feasibility	This technology is commonly used for produced water treatment. Applicable to all types of produced water irrespective of TDS and salt concentrations. It can significantly reduce heavy metals, TOC, BTEX and oil concentrations.	It is applicable for the treatment to all types of produced water irrespective of TDS, organic and salt concentrations. It can reduce oil and grease concentration to 10 ppm	This is a well-established and reliable technology for the removal of COD, BOD, organic and some inorganic compounds present in produced water. It is applicable to all types of produced water irrespective of TDS and salt concentration	This technology is widely used in the petroleum industry, primarily used for conventional oil and gas produced water treatment. It is applicable for produced water with high TO and particulate 7% solids
Energy consumption	Minimal	Does not require energy except to pump water to/from the hydrocyclone	Energy consumption accounts for ~18% of the total operation and maintenance of the oxidation process	Energy required to dissolve gas in the feed stream
Chemical Use	Chemicals required for media regeneration	Chemicals required for media regeneration. Coagulants required	Chemicals such as chlorine, chlorine dioxide, permanganate, oxygen and ozone are required as oxidants	Coagulants may be required to remove target contaminants
Pre and post treatment	Not relevant because adsorption is usually a polishing stage in produced water treatment	Pre-treatment is not required. Post-treatment may be required to remove other contaminants from feed water	No pre- or post-treatment is required	No post-treatment required, but coagulation may be required as a pre-treatment process
Overall cost	Capital accounts for majority of overall cost. For GAC, total cost estimates range from $l.00/l,000. gal ($0.26/1,000 L) for small (1 mgd) systems to about $0.10/l,000 gal ($0.026/1,000 L) for very large systems	Not available. But is highlighted by (SANTOS & ANDRADE, 2005), that the Advantages include the facts that the hydrocyclone are simple, cheap, easy to install, low maintenance cost and low operating cost	Capital cost is about $0.01/gpd. Operation and maintenance cost is about $0.01/bbl.	Not available
Life cycle	It depends on media type. But it might fall in almost 760days, almost 2 years, as minimum time.	Long lifespan	Expected life of chemical metering is 10 years	No information available
Advantages	(1) 80% removal of heavy metals (2) Can achieve nearly 100% water recovery.	(1) Does not require the use of chemicals and energy (2) High product water recovery (3) Can treating any kind of PW reduce oil and grease concentrations to 10 ppm (5) Does not require pre-treatment	(1) It requires minimal equipment (2) No waste is generated from this process (3) It does not require pre- and post-treatment and It has 100% water recovery rate	(1) Product water recovery is almost 100% (2) No post-treatment required
Disadvantages	Waste disposal system is required for spent media or waste produced during media regeneration	(1) Solids can block inlet and scales formation can lead to extra cost in cleaning and (2) Disposal is required for secondary waste generated	(1) Chemical cost may be high; (2) Periodic calibration and maintenance of chemical pump is required (3) Chemical metering equipment is critical for this process	(1) Not ideal for high-temperature feed water (2) Solid disposal is required for sludge

Table 14 - Characterization and comparison of produced water management and treatment technologies applicable for oil and gas PW II.

Technology	MED	Evaporation pond	MPPE technology	Trickling Filter
Feasibility	MED is Removal of trace oil and grease, microbial, soluble organics, divalent salts, acids, and trace solids. Contaminants can be targeted by the selection of the membrane.	This technology is often employed for produced water at full scale. It is applicable to any kind of produced water and its efficiency depends on system design	It is a robust technology applicable for treating both oil and gas produced water. MPPE unit are easy to operate, reliable, fully automated and ideal for process integrated applications	TF develops film of microbial on the surface of packed material to degrade contaminants within water. It's able to remove suspended and trace solids, ammonia, boron, metals etc.
Energy consumption	MED requires both thermal and high use of electrical energy types. Electrical energy consumed is approximately 0.48 kWh/h/bbl and power consumption is 1.3–1.9 kWh/bbl.	None, except pumping is required to get water to/from the pond	None, except pumping is required to get water to/from the pond	High energy consumption cost
Chemical Use	Scale inhibitors are required to prevent scaling. Acid, EDTA and other antiscaling chemicals are required for cleaning and process control	No chemicals required	None	Some chemical cane be used
Pre and post treatment	Pre-treatment is done to remove large suspended solids similar to MSF. This requires screens and rough filtration. Product water stabilization is required because of its low TDS	Typically, no pre- or post-treatment is required. But post-treatment may be required depending on product water quality	Pre-treatment is required for oilfield produced water but not necessary for gas field produced water	Posttreatment is normally required to separate biomass, precipitated solids, dissolved gases etc.
Overall cost	Overall cost is lesser than in MSF. Capital costs ranges from \$ 250 to \$330 per bpd. Operating costs are 0.11/bbl and total unit costs are \$ 0.16/bbl	Not information available	It depends on location	0.28 \$/m cubic, depending on the time
Life cycle	Typically, 20 years	Long lifespan	Long	30 year
Advantages	(1) It requires less rigorous pre-treatment and feed condition compared with membrane technologies (2) It has a long lifespan. (3) Energy requirement is cheaper than using MSF. (4) It can easily be adapted to highly varying water quality	(1) It is very cheap (2) Does not require the use of chemicals and energy	(1,2) No sludge formation, emission (3) Separated hydrocarbons can be reused (4) It is flexible and ideal for process integrated applications and can be used offshore; (5) Hydrocarbon removal efficiency is about .99%	Cheaper, simple and clean technology

	(5) Cost of labour is cheaper than using MSF or membrane technology (6) Good for high TDS produced water treatment (7) Product water quality is high (8) Doesnt require concentrate treatment (9) Product water recovery of up to 67% can be achieved using stacked vertical tube design		(6) Fully automated and can be remotely controlled (7) No biological fouling because of periodic in situ regeneration	
Disadvantages	(1) Typically low product water recovery usually between 20% and 35% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skilled labor required. (5) high energy required, less efficiency for divalent, monovalent salts, viruses etc.	(1) Water volume may be lost due to evaporation (2) Waste disposal is required for materials that settle out of feed water	1) High cost of unit (2) Energy consumption is relatively high compared with other tech. (3) Pre-treatment of oilfield produced water increases the cost of processing	(1) Oxygen requirement, large dimensions of the filter. (2) Sludge waste at the end of the treatment might come out. (3) High energy consumption cost

Source: Adapted based on (ALL Consulting, 2003) and (Igunnu & Chen, 2014)

4.5.3. Evaluation and identification of suitable produced water management and treatment technologies Sasol Petroleum Temane CPF

After characterization of the main seven (8) produced water management and treatment technologies, (1) Multieffect distillation–vapour compression hybrid, (2) Cheemical Oxidation, (3) Adsortion, (4) Macro-porous polymer extraction technology, (5) Evaporation Pond, (6) Gas flotation (7) hydrocyclone and (8) Trickling Filter, in this subchapter will be evaluated the efficiency and efficacy of these technologies remove the contaminate previously identified at produced water samples. These ranking processes are based on (ALL Consulting, 2003) and (Arthur, Langhus, & Patel, 2005) ranking methodology and will be applied in order to find the best and suitable technology for SPT's PW treatment by following steps and calculated using formula (1) above.

Note that, this ranking was made based on individual, historical experience with these two systems and is in no way meant as an endorsement or widespread judgment of either system. It is meant as an illustration the ranking mechanism. This ranking scheme can be applied to a range of technological options for treating produced waters. The ranking can help the oil and gas operator choose between options, but of course an important part of the decision will depend on the requirements for the chosen end use for the water.

Step 1 – Evaluating the ability to remove contaminants

At this step, will be evaluated the ability of the selected technologies to remove contaminants and how complex or simples they are. The simplest method to express the performance of a treatment technology is the removal of contaminants in percentage and can be ranked in five categories.

Table 15 - Evaluating the ability to remove contaminants found in Sasol PW

Technology	**Ranking Range:** from 5 (>95) to 1 (<50)				
	>95%	**90-95%**	**75-90%**	**50-75%**	**< 50%**
Adsorption	-	4	-	-	-
Hydrocyclone	-	4	-	-	-
Chemical Oxidation	5	-	-	-	-
Gas Flotation	5	-	-	-	-
MED	-	4	-	-	-
Evaporation pond	-	-	-	2	-
MPPE technology	-	4	-	-	-
Trickling Filter	-	-	3	-	-

Source: Autor (2020)

According the data in table ***Table 15*** above (step 1) is possible to find that the Chemical oxidation and Gas flotation has high ranking of more than 95% [rank 5], in term of contaminant removal, they a capable to remove contaminant such us removal of heavy metals, COD, BOD, organic and some inorganic compounds present in produced water. It is applicable to all types of produced water irrespective of TDS and salt concentration in comparison to other technologies and they a capable to recover almost 100% of the contaminated water. The MPPE technology and Trickling Filter has less ranking (below 75%) [rank 3 and 2]and rest are between 90-95% [rank 4].

Step 2 – Consumption of resources to achieve desired removal using given technologies

At this step, will be evaluated the ability of the selected technologies in term of consumption of resources as energy, natural resources, cost and effort. This process can be ranked in five categories, from low (5) to high (1) resources consumption.

Table 16 - Evaluating capacity of the technology to consume resources for PW contaminate removal

Technology	**Ranking Range** 5 (low) to 1 (Very High)				
	Low	**Moderated low**	**Moderated**	**High**	**Very High**
Adsorption	-	4	-	-	-
Hydrocyclone	5	-	-	-	-
Chemical Oxidation	-	-	3	-	-
Gas Flotation	-	-	3	-	-
MED	-	-	-	-	1
Evaporation pond	-	4	-	-	-
MPPE technology	-	4	-	-	-
Trickling Filter	-	-	-	-	1

Source: Autor (2020)

Basically, at this step is evaluated the possibility of consumption of resources in terms of effort, cost, energy, natural resources, etc., which must be also considered in ranking. As stated earlier regarding the interdependency of ranking criteria, in the case of Multifactor distillation (MED), requires both thermal and electrical energy types. Electrical energy consumed is approximately 0.48 kWh/h/bbl and power consumption is 1.3–1.9 kWh/bbl. So, both MED and Trickling Filter require high amount of energy to higher recovery rate of 90-95% [rank 4]. For the Chemical oxidation and Gas flotation technology that have high ranking of more than 95%, has a moderate resource consumption, which is likely to one of the best [rank 5]. In this process the hydrocyclone has less demand in term resource consumption, with high ability of removing contaminants (90-95% - [rank 4]).

Step 3 – Requirement of pre- or post-treatment technologies with given technologies:

At this step, will be evaluated the need of additional pre- or post-treatment technologies with given technologies to improve efficiency, to achieve better quality, to handle byproducts. This process can be ranked in five categories, from basic (5) to significant need of additional (1) resources.

Table 17 - Evaluating requirement of pre- or post-treatment technologies with given technologies:

Technology	**Ranking:** 5 (Basic:) to 1 (Significant)				
	Basic	**Primary**	**Secondary**	**Moderated**	**Significant**
Adsorption	5	-	-	-	-
Hydrocyclone	-	4	-	-	-
Chemical Oxidation	-	4	-	-	-
Gas Flotation	-	4	-	-	-
MED	-	-	-	-	1
Evaporation pond	-	-	-	2	-
MPPE technology	-	-	-	-	1
Trickling Filter	-	-	-	2	-

Source: Autor (2020)

For this step, the adsorption [rank 5], gas flotation, hydrocyclone and chemical oxidation [all of them ranking 4], show that these 4 technologies do not require Pre/Post treatment technology due their simplicity, are mostly pass through basic and primary treatment process such as cooling, heating, settling, pH adjustment, softening, chemical addition, de-oiling, suspended solid removal, sand filtration, which is mostly needed to treat Sasol produced water. Besides associate the pre- or post-treatments to contributes to the overall performance by improving the efficiency, to achieve better quality, to handle byproducts, etc., it also adds to cost, facilities, and technological complexity, which are case of other technology with high significant needs [rank 2 and 1].

Step 4 – Durability of the treatment technology:

At this step, will be evaluated the durability of the selected technologies. It finds how the technologies rely on automated activation of pumps and valves to move fluid while other technologies feature simpler flow paths that are gravity-driven. Simpler technologies are easier to maintain and cheaper to operate and it determine the durability. This process can be ranked in five categories, from Less complexity & removal parts (4) and (1) High complexity & high cost one maintenance.

Table 18 - Evaluating the durability of the technology for PW treatment

Technology	**Ranking:** 4 (Less complexity) to 1 (High complexity)			
	Less complexity & removal parts	**Simples automated system**	**Complex automated**	**High complexity & maintenance**
Adsorption	-	3	-	-

Hydrocyclone	-	-	2	-
Chemical Oxidation	4	-	-	-
Gas Flotation	-	-	2	-
MED	-	3	-	-
Evaporation pond	-	3	-	-
MPPE technology	-	3	-	-
Trickling Filter	-	3	-	-

Source: Autor (2020)

The Chemical Oxidation plant in comparison to the other seven (7), presents less removal parts and complex to maintain [rank 4]. While the hydrocyclone and gas flotation [rank 2] and other which rank 3, have more adjustment and continues repair during the time. Some technologies rely on automated activation of pumps and valves to move fluid while other technologies feature simpler flow paths that are gravity-driven. Therefore, the hydrocyclone and other with complex maintenance and more removal parts, they have inability to remove solids, with higher maintenance costs and susceptibility to fouling and blockages from solids buildup. Different Chemical Oxidation, which is more simple and easier to maintain and cheaper to operate. This factor analyzes the degree of durability within a technology.

Step 5 – Mobility of the treatment units:

At this step, will be evaluated the compatibility of treatment technologies to be performed as mobile units benefits the produced water treatment and adds flexibility during oil and gas operations. The mobile ones need less pre-post treatment and less cost will be added into the process. This process can be ranked in five categories, from Less complexity & removal parts (4) and (1) High complexity & high cost one maintenance.

Table 19 - Evaluating the mobility of the treatment units:

Technology	**Ranking:** 2 (Fully mobile) to 1 (Fixed)		
	Fully mobile	**Partially mobile**	**Fixed**
Adsorption	-	1.5	-
Hydrocyclone	-	1.5	-
Chemical Oxidation	-	-	1
Gas Flotation	-	1.5	-
MED	-	-	1
Evaporation pond	-	-	1
MPPE technology	-	1.5	-
Trickling Filter	-	-	1

The Chemical Oxidation, MED, Evaporation and Trickling Filter treatment plants [rank 1], in comparison to the other seven (4) which are partialy mobile [rank 1.5], there fixed with less removal parts. The compatibility of treatment technologies to be performed as mobile units benefits the produced water treatment and adds flexibility during oil and gas operations. If the treatment units are self-contained and mobile, the operator can change locations as water production changes within the field. Many of the individual technologies can be performed by mobile units. However, they may require pre- or post-treatments which can only be performed by fixed units. Such operations are categorized as partially mobile treatments in the following ranking. Therefore, good quality produced water from oil or gas formations may require minimum polishing treatments which can be accomplished by compact modules operated on a mobile treatment truck Such treatments are fully mobile [rank 2]. and **sometime with partially mobile** [rank 1.5].

Step 6 – Level of contaminants in influent produced water

At this step, will be evaluated level of contaminants in influent produced water to be treated. This process can be ranked in five categories, from low (2), medium (1.5) and (1) High.

Table 20 - Evaluating the level of contaminants in influent produced water

Technology	**Ranking:** 2 (Fully mobile) to 1 (Fixed)		
	Low	**Medium**	**High**
Adsorption	-	-	3
Hydrocyclone	-	-	3
Chemical Oxidation	-	-	3
Gas Flotation	-	-	3
MED	-	-	3
Evaporation pond	-	-	3
MPPE technology	-	-	3
Trickling Filter	-	-	3

Based on the data available on table 17, the level of contaminants in influent produced water is very high and can be ranked 3. According to the (step 5) requirement the collected PW samples shows presence of BTEX, dissolved gases, fine oil particles, trace of heavy metals. The data also show presence of TDS ranging 73000 to 110000 mg/L, above 10,000-35,000 ppm and Total petroleum hydrocarbons (TPH) > 100 ppm (between 140 to 1500 ppm). It shows that the quality of influent produced water also contributes to the overall performance of treatment technologies, because has it has more contaminants more will be expended to treat the water. So, to make an sustainable treatment process will be needed a combination of knowledge, innovative technique and combination of several method to clean properly the water with less cost.

Final Step – Calculation of overall rank based on above ranking criteria:

After estimating ranks of each six steps, with the final formula (see formula 1) is calculated overall rank. Below is presented the overall ranking for each ranking in ***Table 21***.

$$\mathrm{OR} = \frac{(\mathrm{STEP\ 1} + \mathrm{STEP\ 2} + \mathrm{STEP\ 3} + \mathrm{STEP\ 4} + \mathrm{STEP\ 5})}{\mathrm{STEP\ 6}}$$

Table 21 - Calculation of overall rank for technology performance

Calculation of overall rank	Adsorption	Hydrocyclone	Chemical Oxidation	Gas Flotation	MED	Evaporation pond	MPPE technology	Trickling Filter
Step 1: Removal efficiency	4	4	5	5	4	2	4	3
Step 2: Resources consumption	4	5	3	3	1	4	4	1
Step 3: Pre/post treatment requirement	5	4	4	4	1	2	1	2
Step 4: Durability of system	3	2	4	2	3	3	3	3
Step 5: Mobility of treatment	1.5	1.5	1	1.5	1	1	1.5	1
Step 6: Level of contaminants in feed	3	3	3	3	3	3	3	3
OVERALL RANK	**5.8**	**5.5**	**5.7**	5.2	3.3	4	4.5	3.3

Based on the ranking process, as shown one ***Table 21*** above, the results indicate better performance to the following treatments technologies: Adsorption [ranking 5.8], Chemical Oxidation [ranking 5.7] and Hydrocyclone [ranking 5.5], due the higher-ranking technologies, higher treatment efficiency and do not require Pre/Post treatment technology and simple to manage. Most of these treatment technologies are applicable to all types of produced water irrespective of TDS and salt concentrations. It can significantly reduce heavy metals, TOC, BTEX, oil concentrations, COD, BOD, organic & inorganic compounds and despite they mostly pass through basic and primary treatment process such as cooling, heating, settling, pH adjustment, softening, chemical addition, de-oiling, suspended solid removal, which is needed to treat Sasol water.

For these three technologies, Energy consumption are basically minimal and might reach almost approximately 18% of the total operation and maintenance of the oxidation process. Some chemicals such as chlorine, chlorine dioxide, permanganate, oxygen and ozone might be used as oxidants. The cost for operation and maintenance are not so high in comparison to the others technology, due to their simplicity.

For chemical oxidation the capital cost is about \$0.01/gpd and operation & maintenance cost is about \$0.01/bbl. For adsorption system, mainly for granular activated carbon (GAC) adsorption, total cost estimates range from about \$l.00/l,000gal (\$0.26/1,000 L) for small (1 mgd) systems to about $0.10/l,000 gal ($0.026/1,000 L) for very large systems. So, basically, the capital cost accounts for majority of overall cost. But for hydrocyclone no much data is available, but is highlighted by Santos & Andrade 2005), that the advantages include the facts that the hydrocyclone are simple, cheap, easy to install, low maintenance cost and low operating cost.

Beside all the similarities and advantages, the main advantage of selected systems, is that they do not require pre- and post-treatment and has 100% water recovery rate, and they are capable to remove almost 80% of contaminants in the water. There is a huge difference in term of life cycle of the systems, adsorption has almost 2 years of lifetime before any maintenance and this process can additionally produce liquid or water residues chemical when the media (the absorbent) is being regenerated or cleaned. The chemical absorption system can reach 10 years before change the chemical metering and it doesn't requires minimal equipment, and no waste is generated from this process. While the hydrocyclone have long lifespan, more than 7 years, but solids can block inlet and scales formation can lead to extra cost in cleaning and disposal is required for secondary waste generated. In this case, the chemical absorption and hydrocyclone systems have more advantage, more lifetime, less residue production, than the absorption one.

Whether going through ranking results, in my point of view, the company should select any of the three select technologies depending on the needs and advantages, for example:

1) By choosing the adsorption system, they would get some advantage, the capability of the system removing more contaminates TDS and salt concentrations, reduce heavy metals, TOC, BTEX, oil concentrations and other organic & some inorganic compounds, which are basically the common contaminates available in produced water for Sasol petroleum Temane. But the backward would be the short interval of maintenance time, less than 2 years and additional cost would be incurred for and high amounts of residues that the system would generate when the system maintenance is being carried out.

2) By choosing the chemical absorption, the company would get a system with more life time, high performance in term of treatment and water recovery, and addition cost would be added for pre or post treatment, but it would need to inject additional cost treat some contaminates that there are not capable, such as, the efficiency of removing heavy metal, TDS, pH adjustment and BTEX removal.

3) By choosing Hydrocyclones, the physical method to separate solids from liquids based on the density of the solids to be separated. Hydrocyclones can remove particles in the range of 5–15 mm and have been widely used for the treatment of produced water. They are used in combination with other technologies as pre-treatment process. They have a long lifespan and do not require chemical use or pre-treatment of feed water. A major disadvantage of this technology is the generation of large slurry of concentrated solid waste.

It's important to consider that, whether choosing adsorption, chemical oxidation, hydrocyclone or other less ranked technologies (gas flotation, MED, evaporation pond, MPPE technology, trickling filter), is important to consider that most of these technologies are effective on treating all types of produced water irrespective of TDS, organic and salt concentrations, but most of them are not able to control the pH, removing metal and control the hardness of the water. Therefore, any of these treatment technologies can be employed, but to be effective and able treat not only the TDS, heavy metals, Total Hydrocarbon Content, BTEX, other organic & some inorganic compounds, but also other parameters, additional process is needed and it can be added in the process, to cover or remove another contaminant that the technologies is not able remove or adjust. The pH correction is important of the water, which is one of the reasons of corrosion process.

For pH correction can be injected in treatment process the Soda ash/sodium hydroxide. This treatment method is used if water is acidic (low pH). Soda ash (sodium carbonate) and sodium hydroxide raise the pH of water to near neutral when injected into a water system. Unlike neutralizing filters, they do not cause hardness problems in treated water. Injection systems are a point-of-entry system. A corrosion-resistant chemical feed pump injects soda ash or sodium hydroxide solution into the water to raise the pH. The solution should be fed directly into the well to protect the well casing and pump from corrosion. If the water needs to be disinfected as well as neutralized, dual treatment is possible within the injection system by adding a chlorine solution (sodium hypochlorite) along with the neutralizing chemical. Injection systems can treat water with a pH is around or lower 4 (Drinking Water Treatment – pH Adjustment, 2019).

CHAPTER V

5.0. GENERAL CONCLUSIONS AND RECOMENDATIOS

5.1. General conclusions

The corrosion process of the pipeline and the problem of environmental pollution generated by influents and produced water from Sasol Petroleum Temane has developed on a large scale due to the increase in the level of production.

According to the samples and results from this study, following can be highlighted that:

- The produced water from Sasol Petroleum Temane contain high level of total dissolved solids, conductivity, total suspended solids, around six (6x) time higher than the what was established by IFC & FAO standards and MICOA legislation, before launch to the environment. The PW results were also showing high amount of iron, total hydrocarbon content and high acidity in produced with pH reaching 4.7.
- It was also possible to find that the presence of corrosion inhibitor, XLAmine and Biocide, was not so effective and efficient on reduction corrosion process because it did not make changes on some parameters present in water like TDS, TSS, Iron, BTEX, although it changed the pH by lowering, becoming the water more acidy. But different aspect happens with bacteria counts, the injection of XLAmine and Biocide in the produced water only affected efficiently the quality of the water by reducing the amounts of bacteria count.
- Environmentally, it was possible to find that the presence of TSS containing small residual hydrocarbon components, and, when it is contact with water create emulsion, that clogs the pipeline and reservoir, blocking it and creating corrosion. While the presence of TDS and TSS indicates high salt content, alkalinity or hardness and can consequently forming encrustation and corrosion of metallic surfaces of industrial equipment. The lowering pH accelerates the rate of corrosion. Besides these problems, if this contaminated water is launched into the environment can contaminate the reception body, so, this water would not need treatment, before discharge it.
- Among all produced water management and treatment technology, there were selected as alternatives technology, the adsorption, chemical oxidation and hydrocyclone technologies. They have capability of removing more contaminates such as TDS and salt concentrations,

reduce heavy metals, TOC, BTEX, oil concentrations and other organic & some inorganic compounds, although the adsorption has short lifespan of 2 years than the more 10 years chemical oxidation and hydrocyclone. As an alternative to make these technologies more effective it can be added can be injected in treatment process the Soda ash/sodium hydroxide for pH correction in order control acidity of water.

- As alternative can be also used other technologies such as gas flotation, multieffect distillation (MED), evaporation pond, Macro-porous polymer extraction (MPPE), trickling filter which are more effective on removal of dissolved and dispersed hydrocarbons, achieving 99% of efficiency one removal of BTEX, PAHs and aliphatic hydrocarbons with high cost of maintenance.

5.2. Recommendations

- The process of ranking the treatment technology used in this study give important and helpful knowledge one how to find a suitable technology for any industry. However, this process would be more effective if cost estimation of the selected technology would be put in place in order find adequacy of the technology with the reality situation.
- It is observed that it would be necessary to conducting further research by the company in order to evaluate in deep application of the selected technologies, if needed.
- The effectiveness and practical application of the selected technology only can be effective after a technical and economic feasibility study. Therefore, is recommended to company to do additional laboratory analysis of the water to find other parameters that influence significantly to quality of the water, such as heavy metal including Arsenic, cadmium, chromium, copper, lead, mercury, nickel, sodium, and zinc, detailed BTEX analysis, Chloride, Temperature and go deep on technical and economic feasibility study.
- Besides the selected technologies, it recommended that the Sasol Petroleum Temane Central Processing Facility (CPF) or the academy to study another alternative water management, treatment technologies or other natural production that would help one reduction of other contaminants, not only bacteria count, but also the suspended, dissolved solid, TOC and adjustment of pH.

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APPENDICES

Table 22 – Limit allowed by different regulations for discharging of PW from oil & gas unit

Parameter [16]	Maxim value based on IFC (2014)	Maxim value based on MICOA (2004)	Maxim value based on FAO (2012)
PH	6-9	6-9	6-9
BOD	25	30	50
COD	125	150	-
TSS	35	30	50
Total hydrocarbon content:	10	-	
Phenols	0.5	0.5	0.5
Sulfides:	1	1	~ 1
Heavy metals (total)[17]:	5	0.1-0.5	-
Chlorides:	600-1200	-	750 max.
Temperature (°C)	•	•	~40
Density [18]	1020 kg/m^3 = ~ 1.02 g/cm^3 = ~1020 mg/l		
TDS[19]	670 -1675mg/l		
Conductivity	1000 -2500 µS/cm		
Salinity [20]	40 ‰ = ~ 400%= ~ 4000000mg/l		

Source: adapted from IFC (2014), (MICOA, 2014) and (FAO, 2012)

Table 23 - Determinant impact parameter of pw to the facilities equipment and environment.

Parameter[21]	Impact to the environment[22]
PH and Temperature	Lower PH will significantly increase the corrosion rate of the steal, pipeline on any machinery covered by metal. Similarly, by increasing temperature, the corrosion rate will increase.
BOD	BOD is generated from compounds of fatty acids - Produced water can be very toxic, expressed by as acute or chronic toxicity.
COD	COD is generated from compounds of fatty acids - Produced water can be very toxic, expressed by as acute or chronic toxicity.
TSS	Total Suspended Solid and Dissolved element which are the mainly represented by CO2, H2S, are the major component that result in salt water. If these two elements are available, they can result in sweet corrosion for CO2 and sour Corrosion for H2S in presence of water.
Conductivity & TDS	Conductivity in join of different inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Conductivity and salinity have a strong correlation. As conductivity is easier to measure, it is used in algorithms estimating salinity and TDS, both of which affect water quality and aquatic life. Total dissolved solids (TDS) value is a measure of inorganic and organic materials present in water, of which salt forms the principal constituent. Waters with high TDS cause cells to shrink, disrupt organisms' movement, and make them afloat or sink beyond their normal range. High TDS value indicates high alkalinity or hardness and can consequently affect taste of the water column and main factor of corrosion one pipeline and equipment. Elevated TDS can cause "mineral tastes" in drinking water. Corrosion or encrustation of metallic surfaces by waters high in dissolved solids causes problems with industrial

[16] Parameters are in milligrams per liter, except for pH and temperature

17 Heavy metals include: Arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, vanadium, sodium and zinc.

[18] Density based on (Duraisamy, Beni , & Henni, 2013)

[19] Converted from 1000-2500 µS/cm to (mg/l) using Conductivity (µS/cm) x 2/3 = Total Dissolved Solids (mg/l), based on (EPA, 2001) , (Surface Water Regulations, 1989) and (Drinking Water Directive, 98/83/EC) from (EPA, 2001)

[20] (EPA, 2001)

[21] milligrams per liter, except for pH and temperature (in degree celcius)

[22] if the produced water is discharged into the environment or reception body (surficial and underground water, soil and livestock) high amount in element composition not allowed by requirement

	equipment and boilers as well as domestic plumbing, hot water heaters, toilet flushing mechanisms, faucets, and washing machines and dishwashers.
Total hydrocarbon content	Produced water from gas production tend to have higher content of low molecular weight aromatic hydrocarbon such as benzene, toluene, ethylbenzene, and xylene (BTEX) than produced water from oil production. Studies indicate that the produced water discharge from gas/condensate platform are about 10 times more toxic than produced water discharged from oil platform.
Sulfides	Produced water from sour oil/gas wells may contain high concentrations of sulfide and elemental sulfur. When the Sulfides get in contact with water it tends to form salty water, the main source of corrosion.
Heavy metals (total)[23]:	– Some metals and higher molecular weight aromatic and saturated hydrocarbons may accumulate in sediments near the produced water discharge, possibly harming bottom living biological communities – Most of metal, such as sodium are major dissolved constituent in most produced waters and it causes substantial degradation of soils through altering of clays and soil textures and subsequent erosion. High sodium levels compete with calcium, magnesium, and potassium for uptake by plant roots. Elevated levels of sodium also can cause poor soil structure and inhibit water infiltration in soil
Salinity	– Salinity is higher in produce water than some sea water which could result to aquatic destruction in fresh water
Chlorides:	– When the Chloride react with water it tends to form salty water. Studies says that the acidity coming from PW form gas are fourth (14) times acid than PW coming from oilfields.

Source: Adapted from VEIL, (2004), KIDNAY & PARRISH (2006), HEDAR & BUDIYONO (2018), (FLORES, 2004), (NEFF, 2002), (NEFF, LEE, & DEBLOIS, 2002) and (JACOBS, GRANT, KWANT, & MARQUENIE, 1992)

[23] Heavy metals include: Arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, vanadium, sodium and zinc.

Table 24 - Comparison of produced water membrane treatment technologies

Technology	Ceramic MF/UF membrane	Polymeric MF/UF membrane	Reverse Osmosis (RO)	Nanofiltration (NF).
Feasibility	Ceramic membranes have been used to treat oilfield produced water and extensively used in other industrial water treatments. They are applicable to all types of produced water irrespective of their TDS and salt concentrations, but produced water with high concentrations may be problematic	Applicable to water with high TDS and salt concentrations and also has the potential to treat produced water however it is extensively used in the municipal water treatment	This technology is used for water softening and removal of metals from wastewater. It is specifically efficient for feed water containing TDS ranging from 500 to 25 000 mg/l. NF is a poor technology for produced water treatment and is inappropriate as a standalone technology	This is a robust technology for seawater desalination and has been employed in produced water treatment. For this technology to be effective in produced water treatment, extensive pre-treatment of feed water is necessary. Several pilot studies failed due to poor pre-treatment and insufficient system integration
Energy consumption	Not available	Not available	It uses electrical energy and its energy requirement is less than what is required in RO systems. Approximately NF system requires 0.08 Kwh/bbl to power its high-pressure pumps	RO use electrical energy for its operation. SWRO requires 0.46 –0.67 KWh/bbl if energy recovery device is integrated. BWRO require less energy than equivalent SWRO system. BWRO requires !0.02–0.13 KWh/bbl of energy to power the system's pumps.
Chemical Use	Ferric chloride, polyaluminium chloride and aluminium sulphate are common coagulants used for pre-coagulation. Acids, bases and surfactants are used in cleaning process	Ferric chloride, polyaluminium chloride and aluminium sulphate are common coagulants used for pre-coagulation. Acids, bases and surfactants are used in cleaning process	Caustic and scale inhibitors are required to prevent fouling. NaOH, H2O2, Na2SO4, HCl, or Na4EDTA are required for cleaning the system	Caustic and scale inhibitors are required to prevent fouling. NaOH, H2O2, Na2SO4, H3PO4, HCl, or Na4EDTA are required for cleaning the system
Pre and post treatment	Cartridge filtration and coagulation are usually used as a pre-treatment. Post-treatment may be required for polishing depending on the product water	Cartridge filtration and coagulation are usually used as a pre-treatment. Post-treatment may be required for polishing depending on the product water	Extensive pre-treatment is required to prevent fouling of membrane. Product water may require remineralization to restore SAR values	Extensive pre-treatment is required to prevent fouling of membrane. Product water may require remineralization or pH stabilization to restore SAR values
Overall cost	Not available	Capital costs depend on feed water quality and size of the polymeric membrane system. Approximate capital cost is \$0.02–\$0.05/ bpd. Approximate Operation and Maintenance costs \$0.02–\$0.05/bpd	Capital cost range from \$35 to \$170/bpd. Operating cost is !\$0.03/bbl	Capital costs of BWRO vary from \$35 to \$170/bpd and operating costs are \$0.03/bbl. Capital costs of SWRO vary from \$125 to \$295/bpd and operating costs are \$0.08/bbl

Table 6. ***Continued***

Life cycle	> 10 years	7 years or more	3–7 years	3–7 years
Advantages	(1) Product water is totally free of suspended solids (2) It can be operated in cross-flow or dead-end filtration mode (3) Product water recovery range from 90% to 100% (4) Ceramic membranes have a longer lifespan than polymeric membranes	(1) Product water is free of suspended solids (2) Product water recovery range from 85% to 100%	(1) It has high pH tolerance (2) System can be operated automatically leading to less demand of skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) It does not require solid waste disposal (5) Water recovery between 75% and 90%	(1) It has high pH tolerance (2) System can be operated automatically leading to less demand of skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) It performs excellently for produced water treatment with appropriate pre-treatment (5) It does not require concentrate treatment as brine generated is usually disposed into sea (6) Product water recovery in SWRO is between 30% and 60%, and between 60% and 85% in BWRO
Disadvantages	(1) Irreversible membrane fouling can occur with significant amount of iron concentration in feed water (2) Membrane requires periodic cleaning (3) Waste generated during backwash and cleaning processes require disposal/recycling or further treatment	(1) Membrane requires periodic cleaning (2) Waste generated during backwash and cleaning processes require disposal/ recycling or further treatment	(1) It is highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures in excess of 458C (3) It requires several back washing cycles	(1) It is highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures in excess of 458C

Source: Adapted based one (ALL Consulting, 2003) and (Igunnu & Chen, 2014)

Table 25 - Comparison of produced water thermal treatment technologies

Technology	MFS	MED	VCD technology	MED–vapor compression hybrid	Freeze thaw evaporation
Feasibility	This is a mature and robust desalination technology that can be employed for produced water treatment. MSF is applicable to all types of water with high TDS range up to 40 000 mg/l	This is a mature and robust desalination technology that can be employed for produced water treatment. MED is applicable to all types of water and a wide range of TDS	This is a mature and robust seawater desalination technology. It is applicable to all types of waste water with TDS level greater than 40 000 mg/l. Various enhanced VCD have been applied in produced water treatment	A mature desalination technology that has been employed in produced water treatment. It is usually employed for treating water with high TDS. In future product, water quality may be increased. For example, product water recovery of 75% was achieved by GE using brine concentrator and analyzer	This is a mature and robust technology for produced water treatment. It does not require infrastructure. This process requires favorable soil conditions, a significant amount of land and a substantial number of days with temperatures below freezing
Energy consumption	Electrical energy required ranges from 0.45 kWh/bbl to 0.9 kWh/ bbl. Thermal energy required is estimated at 3.35 kWh/bbl . Overall energy required for MSF ranges from 3.35 to 4.70 kWh/bbl	MED requires both thermal and electrical energy types. Electrical energy consumed is approximately 0.48 kWh/h/bbl [51] and power consumption is 1.3–1.9 kWh/bbl	VCD requires both thermal and electrical energy. For desalination, power energy consumption is 1.3 kWh/bbl [53]. Electricity consumption is 1.1 kWh/bbl for mechanical vapour compression (MVC) and to achieve zero-liquid discharge energy demand is 4.2 – 10.5 kWh/bbl	It uses both thermal and electrical energy. Power consumption for desalination is !0.32 kWh/bbl [49]. To achieve zero-liquid discharge energy consumption is around 4.2–10.5 kWh/bbl	It uses electrical energy, but data are not available
Chemical Use	EDTA, acids and other anti-scaling chemicals are used to prevent scaling. pH control is also necessary to prevent corrosion	Scale inhibitors are required to prevent scaling. Acid, EDTA and other anti-scaling chemicals are required for cleaning and process control	Scale inhibitors and acids are required to prevent scaling. EDTA and other anti-scaling chemicals are required for cleaning and process control. Corrosion is prevented by pH control	Scale inhibitors are required to prevent scaling. Acids, EDTA and other anti-scaling chemicals are required for cleaning and process control. Corrosion is prevented by pH control	None
Pre and post treatment	Pre-treatment is done to remove large suspended solids. This requires screens and rough filtration. Product water stabilization is required because of its low TDS	Pre-treatment is done to remove large suspended solids similar to MSF. This requires screens and rough filtration. Product water stabilization is required because of its low TDS	Pre-treatment and post-treatments are required in order to avoid fouling and because of low TDS level in product water, respectively	It requires a less rigorous pre-treatment compared with membrane technologies. Lime bed contact post-treatment is required because of low TDS of product water	It requires minimal pre- and post-treatment depending on product water quality and discharge standards

Table 7. ***Continued***

Overall cost	Capital costs vary between $250 and $360 per bpd. Operating costs are $0.12/bbl and total unit costs are $0.19/bbl [51]	Overall cost is lesser than in MSF. Capital costs ranges from $ 250 to $330 per bpd. Operating costs are 0.11/bbl and total unit costs are $ 0.16/ bbl [51]	Capital costs of vapor compression for sea water desalination ranges from $140 to 250 per bpd depending on various factors. Operating costs are !0.075/bbl and total unit costs are $0.08/bbl for seawater desalination [51]	Capital cost is $250 per bbl per day [51]. Operation costs depend on the amount of energy consumed	It depends on location
Life cycle	Typically, 20 years but most plants operate for more than 30 years	Typically, 20 years	Typically, 20 years but may operate for more years	Typically, 20 years but may be longer if made of materials with high corrosion resistance	Expected lifespan is 20 years
Advantages	(1) It requires less rigorous pre-treatment and feed condition compared with membrane technologies (2) It has a significantly long lifespan. (3) MSF system can withstand harsh conditions (4) It can easily be adapted to highly varying water quality (5) Cost of labour is cheaper than using membrane technology (6) Good for high TDS produced water treatment (7) Product water quality is high with TDS levels between 2 mg/l and 10 mg/l.	(1) It requires less rigorous pre-treatment and feed condition compared with membrane technologies (2) It has a long lifespan. (3) Energy requirement is cheaper than using MSF. (4) It can easily be adapted to highly varying water quality (5) Cost of labour is cheaper than using MSF or membrane technology (6) Good for high TDS produced water treatment (7) Product water quality is high (8) Doesnt require concentrate treatment (9) Product water recovery of up to 67% can be achieved using stacked vertical tube design	(1) Applicable to all types of water and water with high TDS 40 000 mg/l. (2) It is a smaller unit compared with MS F and MED (3) It has high ability to withstand harsh conditions (4) It does not require special concentrate treatment (5) Pre -treatment is less rigorous compared with membrane treatment	(1) It has high product water quality (2) Excellent treatment technology for produced water with high TDS and zero liquid discharge (3) System can withstand harsh condition	(1) Excellent for zero liquid discharge (2) It requires low skilled labour, monitoring and control (3) It is highly reliable and can be easily adapted to varying water quality and quantity
Disadvantages	(1) Low product water recovery usually between 10 and 20% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem	(1) Typically low product water recovery usually between 20% and 35% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skilled labor required	(1) Typically low product water recovery is usually around 40% (2) It is not flexible for varying water flow rates (3) Scaling and corrosion can be a Problem operate system (4) High level of skills are required to	(1) Not applicable to produced water wells point source (2) Being a hybrid design, it requires very highly skilled labour	(1) Cannot treat produced water with high methanol concentration (2) Moderate product water quality containing !1000 mg/l TDS (3) Can only work in winter time and in places with below freezing temperatures (4) A significant amount of land is required (5) It generates secondary waste streams

Source: Adapted based one (ALL Consulting, 2003) and (Igunnu & Chen, 2014)

Table 26 - Comparison of other produced water treatment technologies I.

Technology	BAF	Media Flotation	Gas Flotation	Evaporation pond	MPPE technology
Feasibility	This is a well-established technology that has been used for produced water treatment [30]. It is mostly effective for feed water with chloride levels below 6600 mg/l	This technology has been extensively used for produced water treatment. It is applicable for all TDS and independent of salt concentration	This technology is widely used in the petroleum industry, primarily used for conventional oil and gas produced water treatment. It is applicable for produced water with high TO and particulate 7% solids	This technology is often employed for produced water at full scale. It is applicable to any kind of produced water and its efficiency depends on system design	It is a robust technology applicable for treating both oil and gas produced water. MPPE unit are easy to operate, reliable, fully automated and ideal for process integrated applications
Energy consumption	1–4 KWh.	Minimal energy required. Energy is required for backwashing filters	Energy required to dissolve gas in the feed stream	None, except pumping is required to get water to/from the pond	None, except pumping is required to get water to/from the pond
Chemical Use	None	Chemicals required for media regeneration. Coagulants required	Coagulants may be required to remove target contaminants	No chemicals required	None
Pre and post treatment	Sedimentation may be required as a pre-treatment process. Typically, post-treatment is not required	None required	No post-treatment required, but coagulation may be required as a pre-treatment process	Typically no pre- or post-treatment is required. But post-treatment may be required depending on product water quality	Pre-treatment is required for oilfield produced water but not necessary for gas field produced water
Overall cost	Not available but capital accounts for majority of overall cost	Not available	Not available	Not information available	It depends on location
Life cycle	Long lifetime expected	It depends on media type	No information available	Long lifespan	Long
Advantages	(1) Water recovery is almost 100% (2) Easy to adapt to wide range of water quality and quantity (3) Little need for maintenance. (4) Does not require post-treatment (5) Some BAF does not require any equipment.	(1) .90% oil and grease removal efficiency (2) Can achieve nearly 100% water recovery	(1) Product water recovery is almost 100% (2) No post-treatment required	(1) It is very cheap (2) Does not require the use of chemicals and energy	(1,2) No sludge formation, emission (3) Separated hydrocarbons can be reused (4) It is flexible and ideal for process integrated applications and can be used offshore; (5) Hydrocarbon removal efficiency is about .99% (6) Fully automated and can be remotely controlled (7) No biological fouling because of periodic in situ regeneration
Disadvantages	Solid disposal required for sludge that accumulates in the sedimentation basin can cost up to 40% of the overall cost	Waste disposal system required for spent media or waste produced during media regeneration	(1) Not ideal for high-temperature feed water (2) Solid disposal is required for sludge	(1) Water volume may be lost due to evaporation (2) Waste disposal is required for materials that settle out of feed water	1) High cost of unit (2) Energy consumption is relatively high compared with other tech. (3) Pre-treatment of oilfield produced water increases the cost of processing

Source: Adapted based one (ALL Consulting, 2003) and (Igunnu & Chen, 2014)

Table 27 - Comparison of other produced water thermal treatment technologies II.

Technology	Adsorption	Hydrocyclone	Chemical Oxidation
Feasibility	This technology is commonly used for produced water treatment. Applicable to all types of produced water irrespective of TDS and salt concentrations. It can significantly reduce heavy metals, TOC, BTEX and oil concentrations. It is best used as a polishing step rather than a major treatment process in order to avoid rapid consumption of adsorbent material	It is applicable for the treatment to all types of produced water irrespective of TDS, organic and salt concentrations. It can reduce oil and grease concentration to 10 ppm	This is a well-established and reliable technology for the removal of COD, BOD, organic and some inorganic compounds present I produced water. It is applicable to all types of produced water irrespective of TDS and salt concentration
Energy consumption	Minimal	Does not require energy except to pump water to/from the hydrocyclone	Energy consumption accounts for ~18% of the total operation and maintenance of the oxidation process
Chemical Use	Chemicals required for media regeneration	Chemicals required for media regeneration. Coagulants required	Chemicals such as chlorine, chlorine dioxide, permanganate, oxygen and ozone are required as oxidants
Pre and post treatment	Not relevant because adsorption is usually a polishing stage in produced water treatment	Pre-treatment is not required. Post-treatment may be required to remove other contaminants from feed water	No pre- or post-treatment is required
Overall cost	Not available but capital accounts for majority of overall cost. For adsorption system, mainly the Granular Activated Carbon, in these cases, total cost estimates for GAC systems range from about $l.00/l,000gal ($0.26/1,000 L) for small (1 mgd) systems to about $0.10/l,000 gal ($0.026/1,000 L) for very large systems	Not available	Capital cost is about $0.01/gpd. Operation and maintenance cost is about $0.01/bbl.
Life cycle	It depends on media type	Long lifespan	Expected life of chemical metering is 10 years
Advantages	(1) 80% removal of heavy metals (2) Can achieve nearly 100% water recovery.	(1) Does not require the use of chemicals and energy (2) High product water recovery (3) Can reduce oil and grease concentrations to 10 ppm (4) Can be used for treating any kind of produced water (5) Does not require pre-treatment	(1) It requires minimal equipment (2) No waste is generated from this process (3) It does not require pre- and post-treatment (4) It has 100% water recovery rate
Disadvantages	Waste disposal system required for spent media or waste produced during media regeneration	(1) Solids can block inlet and scales formation can lead to extra cost in cleaning (2) Disposal is required for secondary waste generated	(1) Chemical cost may be high. (2) Periodic calibration and maintenance of chemical pump is required (3) Chemical metering equipment is critical for this process

Source: Adapted based one (ALL Consulting, 2003) and (Igunnu & Chen, 2014)